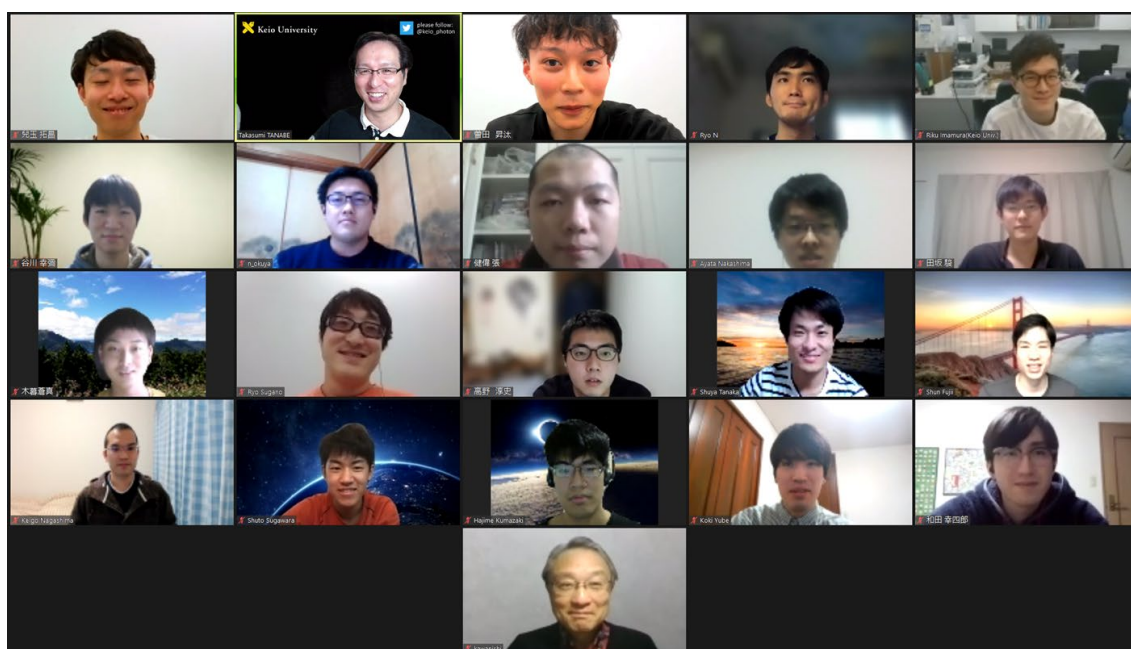




Annual Report on Research Activities 2021 (Volume 11)



Tanabe Photonic Structure Group,
Department of Electronics and Electrical Engineering,
Faculty of Science and Technology, Keio University

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Foreword

Thank you for your continued interest in and support for the research and educational activities of the Tanabe Photonic Structures Laboratory in the Department of Electronics and Electrical Engineering, Faculty of Science and Technology, Keio University.

During the 2021 academic year, the COVID-19 pandemic continued to limit our research activities and opportunities for students to interact. As online meetings and conference presentations became part of our routine, we came to appreciate anew the value of meeting fellow researchers and discussing ideas in person. For students in particular, listening to other researchers and exploring different perspectives is just as important as presenting their own work. To encourage these exchanges, we held two online events in August: a workshop on integrated optical frequency combs and a joint meeting of photonics laboratories at Keio University. Poster sessions and informal gatherings provided opportunities for students from different laboratories and institutions to meet and exchange ideas. We will continue to create such opportunities, even when circumstances limit how we can meet.

We also received NEDO funding for a new project on developing and integrating optical frequency comb sources. Our aim is to use the multiple wavelengths generated by optical microresonators in energy-efficient optical communication systems. In addition to developing the sources themselves, we are working to integrate them with silicon photonic devices. We received funding for research on photonic crystal spectrometers as well. These projects extend our work into communications and measurement technologies while building on our core expertise in controlling light with microstructures. I am grateful to our research partners for their cooperation and to our students for the sustained effort that makes this work possible.

This report presents our research activities and findings from the 2021 academic year. Our students led the preparation, and we kept editorial changes to a minimum to preserve their words. We hope you will find this account of our work informative and engaging. If you would like to learn more about our activities, please do not hesitate to contact us. Thank you for your continued support.



March 2022
Takasumi Tanabe, Professor
Department of Electronics and Electrical Engineering,
Keio University

Lab Members (Names and their positions after graduation)

Professor: Takasumi Tanabe

Research professor: Satoki Kawanishi

Technical staff: Hajime Kumazaki

Secretary: Atsuki Shinki (2020/7 -)

PhD Students:

Riku Imamura Continues in the graduate school of Keio University (PhD)

Master 2nd Grade: (The class of 2019)

Shuya Tanaka	Graduated from the graduate school of Keio University (Sep. 2021)
Shota Sota	Graduated from the graduate school of Keio University
Keigo Nakajima	Graduated from the graduate school of Keio University
Koki Yube	Graduated from the graduate school of Keio University
Koshiro Wada	Graduated from the graduate school of Keio University
Takumasa Kodama	Graduated from the graduate school of Keio University
Shun Tasaka	Graduated from the graduate school of Keio University

Master 1st Grade: (The class of 2020)

Zhang Jianwei	Continues in the graduate school of Keio University
Soma Kogure	Continues in the graduate school of Keio University
Ryo Sugano	Continues in the graduate school of Keio University
Shuto Sugawara	Continues in the graduate school of Keio University
Ayata Nakashima	Continues in the graduate school of Keio University

Bachelor 4th Grade: (The class of 2021)

Yuki Tate	Graduates from Keio University
Koki Tanikawa	Continues in the graduate school of Keio University
Atsushi Takano	Continues in the graduate school of Keio University
Ryo Nishihata	Graduates from Keio University
Nao Okuya	Graduates from Keio University

Short-term exchange student: (Sep. 2021 -)

David Moreno Gallego De La Sacristana	Valencia University, Spain
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Research Activities

Development of Photonic Crystal Spectrometer Using Fabrication Error

Takumasa Kodama (M2) Ryo Sugano(M1)

The presence of fabrication errors often degrades the performance of nanophotonic devices. Fabrication error in Photonic crystal waveguide (PCW) often appear as Anderson localization. This report shows that the random localization of light can be used to enhance the resolution of a photonic crystal spectrometer by analyzing the data with deep learning and a global optimization process.

Key words : Photonic crystal, Spectrometer.

1. Background

Photonic crystal (PhC) has a structure periodically changing refractive index, and it has been researched because of its ability to control the propagation of light and to promote light-matter interactions. However, the affect of fabrication error, which is inevitable for nanophotonics devices, limits device performance. Overcoming the problem is an important challenge for device commercialization. The affect of fabrication error with PhC is known to Anderson localization, and the mechanism of localization has been elucidated in a number of previous studies [1]. However, it is still no way to reduce the affect of localization caused by fabrication error, and we may think that the best way is to improve fabrication methods, such as lithography. Recently, research has been conducted to reverse the affects of fabrication errors. Research on random lasers[2] and spectroscopic devices[3] using completely random structures, and research on the application of localization due to fabrication errors to electro-optic modulation[4] have appeared, and these devices can ignore or apply the affects of fabrication errors. However, the product has not yet been put into practical use.

We also have been studying how to take advantage of inherent fabrication errors. Localization in PhC is wavelength-dependent, and the location of localization varies greatly depending on the input wavelength. We have developed a high-resolution spectroscopic device that exploits the affects of fabrication errors in PhC waveguides (PCW).

2. Operation principle

In this study, we used a very simple structure called a chirped photonic crystal waveguide (PCW). Figure 1(a) shows a schematic diagram of the structure. The waveguide width of PCW varies by same intervals, and the mode gap changes in each section. Structural randomness also results in localized light confinement [Figure 1(b)]. Figure 1(c) shows the localization when a 2 nm perturbation is applied to the hole diameter in

simulation. Figure 1(d) shows the image data obtained experimentally. From these images, it can be confirmed that the location of localization varies depending on the input wavelength. Therefore, it is possible to store these patterns for a single wavelength input and reconstruct the input spectrum from the unknown patterns.

Such devices are limited to a resolution of approximately 1.5 nm due to the accuracy of CMOS-compatible processes. In this study, localization patterns are applied to spectral reconstruction to improve the resolution.

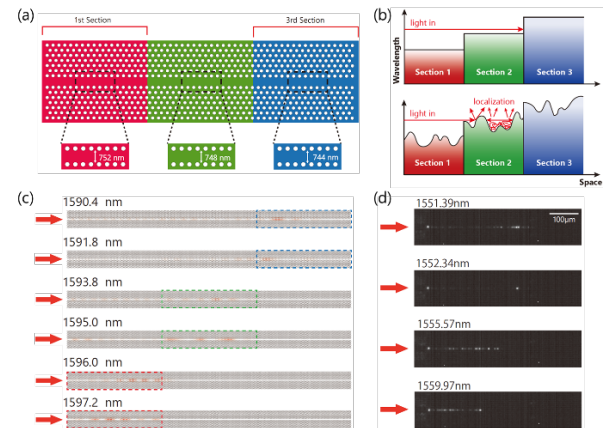


Fig. 1. (a) A chirped PCW. (b) Mechanism of localization. (c) Simulated image using FDTD. The waveguide width varies periodically from 764 nm, 759 nm, and 754 nm. (d) Experimental image. The image was acquired from the top of the slab with an IR camera.

3. Spectrum reconstruction with Deep learning

First, we used deep learning to analyze the spectra. Localization patterns of single wavelength inputs were used as training data. Figure 2(a) shows a schematic of the deep learning algorithm. Figure 2(b) shows the results using simulation data. The wavelength range was 1596.6 nm to 1604.4 nm, and 30 images were prepared for each wavelength class. After training, we achieved an accuracy of 97 % at a resolution of 0.2 nm. Figure 2(c) shows the result using the experimental images, ranging in wavelength from 1584.8 nm to 1595.0 nm. Similarly, we confirmed a high accuracy rate of 98 % at a resolution of 0.2 nm.

By using deep learning to learn localization

patterns caused by structural randomness, we were able to improve performance beyond the resolution limits defined by the device structure. However, two challenges for deep learning were identified: estimating wavelength resolution, and analyzing multiple wavelength inputs. To solve these problems, we employed a new optimization algorithm as a spectral reconstruction mechanism and performed spectral analysis of multi-wavelength input.

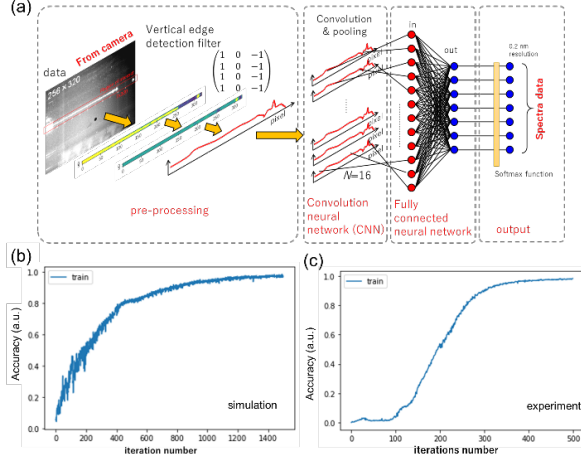


Fig. 2. (a) Schematic of the deep learning algorithm. (b) Training results using simulation images. (c) Results of analysis using experimental data.

4. Multi-wavelength analysis

4.1. Estimation of resolution

we used the spectral correlation function(SCF) to approximate the resolution. SCF is expressed by

$$C(\Delta\lambda) = \frac{\langle I(\lambda, x)I(\lambda + \Delta\lambda, x) \rangle}{\langle I(\lambda, x) \rangle \langle I(\lambda + \Delta\lambda, x) \rangle} - 1$$

$I(\lambda, x)$ is the x^{th} pixel value at wavelength λ . $\langle \dots \rangle$ averaged over λ . Figure 3(a) represents SCF. Since resolution is defined by the full width at half maximum of the SCF, we defined 0.08 nm as resolution.

Since the intensity distribution of multiple inputs $\vec{I}_{\text{multi}}$ is expressed as

$$\vec{I}_{\text{multi}} = \sum_{i=1}^n s_i \vec{I}_{\lambda_i} = \mathbf{T} \vec{S}$$

by linear combination of the intensity distribution $\vec{I}_{\lambda_i} (i = 0 \sim n)$ of the single input. $\vec{S} = [s_1, s_2, \dots, s_n]$ is the intensity at each wavelength in the input light, obtained by sampling the spectrum. The wavelength range is from 1535 nm to 1555 nm, and the data of pixel values on the waveguide are stored in the transition matrix $\mathbf{T}$. Figure 3(b) corresponds to the transition matrix $\mathbf{T}$. The results of the reconstruction of the multi-wavelength spectrum are shown in Figure 3(c,d). Figure 3(c) shows the reconstruction results for a two-wavelength input separated only by 0.16 nm, and Figure 3(d) shows that of a more complex multi wavelength input. The red line is the reference

spectrum measured with optical spectrometer analyzer after splitting the input light with a beam splitter. These results show that the spectra could be reconstructed with a resolution of 0.08 nm in the 20 nm wavelength band.

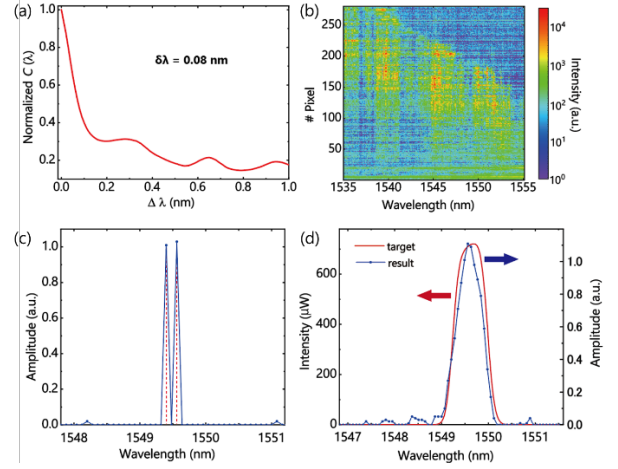


Fig. 3. (a) Spectral correlation function of the intensity distribution averaged over all pixels. (b) Transition matrix of a chirped PCW with randomness. (c) The result of reconstruction with two input spectrum. (d) Reconstructed spectrum of an input with broad spectrum, which has 0.75 nm FWHM.

5. Conclusion

The resolution of photonic crystal waveguide spectrometers is limited by the precision of fabrication process, which is approximately 1.5 nm. We have demonstrated an application of using fabrication errors to improve the resolution to 0.08 nm. A possible future prospect is to use deep learning to advance spectral reconstruction of multi-wavelength input.

Reference

- [1] P. D. García, G. Kiršanskė, A. Javadi, S. Stobbe, and P. Lodahl. Phys. Rev. B **96**, 144201 (2017).
- [2] J. Liu, P. D. Garcia, S. Ek, N. Gregersen, T. Suhr, M. Schubert, J. Mørk, S. Stobbe, P. Lodahl. Nat. Nanotechnology, **9**, 285–289 (2014).
- [3] B. Redding, S. F. Liew, R. Sarma, H. Cao. Nat. Photonics, **7**, 746–751 (2013).
- [4] Y. Ooka, N. A. B. Daud, T. Tetsumoto, T. Tanabe. Opt. Express, **24**, 10, 11199–11207 (2016).

Integrated time-multiplexed heralded single photon sources with coupled resonator quantum memories

Koki Yube (M1)

Heralded single-photon sources have a trade-off between the fidelity of a single photon and the probability of its production. It is known that the trade-off can be overcome by using time-multiplexing, but integrated systems have not yet achieved the low-loss quantum memory required for this technique. In this study, we developed elemental technologies for time-multiplexed single-photon sources by memory of photons using micro optically coupled resonators.

Key words: Heralded single photon source; time multiplexing; Coupled resonators

1. Background

Single photon sources are necessary element for quantum information technology using photons. Practical quantum photon sources are required to be able to operate at room temperature and to emit photons in the communication wavelength band. Heralded single photon sources (HSPSs) may satisfy these conditions and is being actively studied. HSPSs use nonlinear optical effects such as four wave mixing (FWM) and spontaneous parametric down conversion (SPDC) to generate photon pairs in a quantum entangled state, detect one, and output the other as a single photon.

However, since the generation of photon pairs based on the nonlinear optical effect is stochastic, there is a trade-off between the probability of single photon generation and the heralded fidelity. It has been demonstrated in bulk optics that this trade-off can be overcome by using a technique called time multiplexing [1]. Integrated photon sources are required from the viewpoint of applicability, but time multiplexing is not applied because low-loss adjustable delay lines are not realized in the photonic integrated circuits.

The objective of this study is to realize time multiplexing of an integrated heralded single-photon source using a low-loss tunable delay line based on dynamic Q modulation [2] of the coupling resonator of a micro-optical resonator. This year, we report on the development of elemental technologies for dynamic Q modulation and generation of transmitted single photons.

2. High Q edge-toroid resonators

In this research, silicatroid resonators must be fabricated at the edge of the substrate for the convenience of coupling resonators together, and these are called edge-toroid resonators. Figure 1 shows the fabrication process of an edge toroid resonator

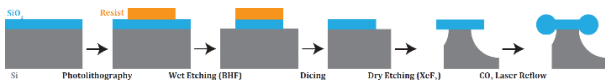


Figure 1: Fabrication process of an edge toroid resonator

In addition to the usual fabrication process of toroid resonators, a dicing process is added for edge toroid resonators. When XeF_2 etching is performed on the diced silicon substrate, the amount of etching on the

edge side increases due to the asymmetry of the silicon between the bulk side and the edge side. It was found that even if CO_2 laser reflow is performed on a silica disk resonator with asymmetric silicon posts, the silica toroids also become asymmetric due to the post shape, causing a low Q. To fabricate symmetrical silicon posts, two diced substrates were etched with their cut surfaces facing each other. This resulted in a symmetrical etching, with a gradual gradient in the amount of silicon between the edge and bulk sides. Figure 2 shows the silicon post geometry before and after the improvement. The Q of the edge toroid resonator before the improvement was about $10^4 - 10^5$, but after the improvement, the Q improved to 10^7 .

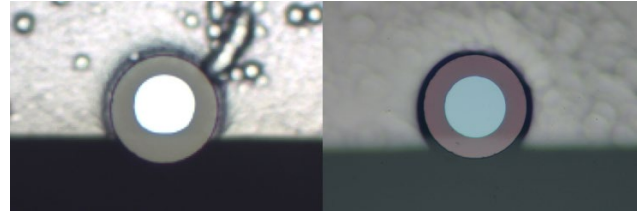


Figure 2: Asymmetric etching due to dicing (left) and symmetric etching after improvement (right)

3. Resonant frequency control by optical Kerr effect

To dynamically control the Q of the coupled resonator, it is necessary to shift the resonant frequency of the resonator using the refractive index change caused by the optical Kerr effect. Figure 3 shows the experimental setup of an optical switch in which the output of the signal light is changed by the input of the control light.

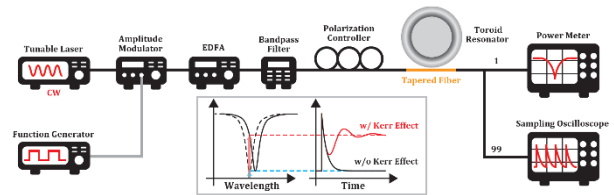


Figure 3: Experimental setup of an optical switch with resonant frequency shift using the optical Kerr effect.

In the initial state, the frequency of the signal light and the resonance frequency are misaligned, but due to the resonance frequency shift by the control light, the frequency of the signal light and the resonance

frequency match, and the signal light is input into the resonator. Figure 4 shows the results of the shift of the resonance frequency depending on the optical intensity of the control light. The amount of frequency shift in the experimental results can be calculated from the results of numerical calculations using coupled mode theory.

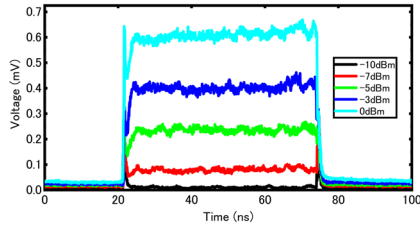


Figure 4: Signal light output intensity change by optical switch with resonance frequency shift using optical Kerr effect.

4. Single Photon Generation by SPDC

In this study, Type-II PPKTP crystals were used as nonlinear crystals to generate SPDC. Thus, the photon pairs produced are generated with two orthogonal polarizations. The excitation wavelength is 780 nm and the wavelength of the photon pair produced is 1560 nm. Hanbury-Brown-Twiss correlation measurements were performed on one of the generated photon pairs. The light from the source is split 50:50 by a beam splitter before detection, and the coincidence of the two detectors is measured. Figure 5 shows the results of the correlation measurement. The horizontal axis is the difference in detection delay between the two detectors, and the large number of coincident photons near 0 confirms photon bunching, since one of the photon pairs produced by SPDC is in the thermal radiation state.

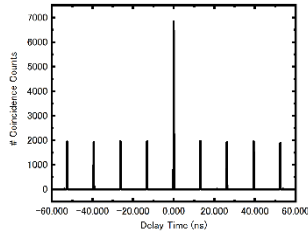


Figure 5: Correlation measurements of one of the photon pairs generated by SPDC.

5. Conclusion

In the previous year, we demonstrated by simulation that by dynamically modulating the coupling Q of a coupled resonator system, it can be used as a variable delay line for low-loss integrated photons. A stochastic model of a space-time multiplexed single photon source with propagation was constructed, and the performance achievable with an integrated single-photon source with propagation was evaluated using the values obtained from simulations of the variable delay line. This year, we developed elemental technologies for the integration of time-multiplexed single-photon sources with propagation. We worked on the development of an edge toroid resonator with high Q , frequency shift by optical Kerr effect for dynamic Q control, and photon pair generation by SPDC for the generation of a single photon with propagation. The Q of the edge toroid resonator was successfully improved by about $10^2 - 10^3$ by improving the etching process. The first prospect for

the future is to time-multiplex an integrated single-photon source with propagation by integrating a system of coupled resonators of the SPDC and the edge-toroid resonator with the frequency shift by the optical Kerr effect, which was developed as an elemental technology for dynamic Q control and propagated single-photon generation.

References

- [1] F. Kaneda, P. G. Kwiat, Sci. Adv. **5**, eaaw8586 (2019)
- [2] W. Yoshiki, Y. Honda, T. Tetsumoto, K. Furusawa, N. Sekine, and T. Tanabe, Sci Rep **7** 10688 (2017).

Study on performance of hydrogen gas sensor using micro-optical resonator under low concentration

Nao Okuya (B4)

Hydrogen gas is currently attracting attention as a promising next-generation energy source. However, hydrogen gas is colorless and odorless, and there is a risk of explosion when the concentration in the atmosphere is 4 to 75%, so it is dangerous for practical application. The realization of a high-sensitivity hydrogen sensor is expected to solve this problem. In this research, we simulated the thermal analysis of multiple micro-optical cavities toward the realization of a heat-conducting sensor using a micro-optical resonator. We compared the performance.

Key words: Micro-optical resonator, hydrogen gas sensor

1. Background

Hydrogen gas is currently attracting attention as a promising next-generation energy source. The reasons for this include high combustion efficiency and no emission of carbon dioxide during combustion. However, hydrogen gas is colorless and odorless, and there is a risk of explosion when the concentration in the atmosphere is 4 to 75%, so it is dangerous for practical application. The realization of a high-sensitivity hydrogen sensor is expected as a solution to this problem.

Hydrogen gas sensors that are currently in practical use have an electric circuit exposed in hydrogen gas, so there is a risk of explosion due to sparks.^[1] However, by using a micro-optical resonator, it is possible to create a safe sensor in which the electric circuit is not exposed in hydrogen gas. However, although a temperature sensor using a micro-optical resonator has been put into practical use, a gas sensor using a micro-optical resonator has not been put into practical use.^[2]

In this research, we aim to put a hydrogen gas sensor into practical use using a micro-optical resonator that uses the principle of a temperature sensor. Therefore, the purpose is to compare the performance of several micro-optical resonators as hydrogen gas sensors by simulation and to show the optimum resonator especially under low concentration. The models of the micro-optical resonator used are silica toroid (SiO₂ toroid) resonator, silicon one-dimensional photonic crystal (Si 1DPhC) resonator, silicon two-dimensional photonic crystal (Si 2DPhC) resonator, and silica one-dimensional photonic crystalline (SiO₂ 1DPhC) resonator.

2. Principle

In this research, sensing is performed using the high thermal conductivity of hydrogen gas. In the micro-optical resonator, heat is generated by light absorption, and the resonance wavelength changes. Since the heat generated at this time dissipates to the surrounding gas, the temperature of the resonator depends on the thermal conductivity of the surrounding gas. Since the concentration of the object to be measured can be known from the conductivity of the gas, sensing is performed by measuring the amount of change in the resonance wavelength.

The calorific value due to heat absorption of a resonator made of silica is expressed by the following equation.^[3]

$$q_{in} = \eta P_{in} Q \frac{\alpha_{abs} \lambda_0}{2\pi n} \quad (1)$$

Here, η is the coupling efficiency, P_{in} is the power of the input light, Q is the Q factor of the resonator, α_{abs} is the absorption coefficient, and λ_0 is the resonance wavelength.^[4]

The heat generated by the absorption of a resonator made of silicon is represented by the linear absorption and the two-photon absorption, but the heat generated by the linear absorption is negligibly smaller than the heat generated by the two-photon absorption. Therefore, the calorific value is expressed by the following equation.

$$q_{in} = P_{in} + 2 \left\{ \frac{n\pi^2 V_{eff}}{\beta \lambda_0^2 Q^2} - \sqrt{\left(\frac{n\pi^2 V_{eff}}{\beta \lambda_0^2 Q^2} \right)^2 - \frac{n\pi^2 V_{eff}}{\beta \lambda_0^2 Q^2} P_{in}} \right\} \quad (2)$$

Here, V_{eff} represents the effective volume of the resonator, and β represents the two-photon absorption coefficient.

After calculating the calorific value, COMSOL is used to investigate the relationship between the hydrogen concentration and the resonator temperature by simulation.

The shift amount of the resonance wavelength due to the temperature change is expressed by the following equation.

$$\Delta\lambda = \lambda_0 \frac{1}{n} \frac{dn}{dT} \Delta T(t) \quad (3)$$

Here, $\Delta T(t)$ is the amount of temperature change, and $\frac{dn}{dT}$ is the TO coefficient.

The sensor sensitivity is evaluated by the amount of shift of the resonance wavelength with respect to the line width of the resonance wavelength. Therefore, the sensor sensitivity is evaluated using the following equation obtained by dividing equation (3) by the line width $\delta\lambda$ of the resonance wavelength.

$$\Delta\lambda' = \frac{\Delta\lambda}{\delta\lambda} \quad (4)$$

3. Simulation

Thermal analysis simulation of the optical cavity was performed using COMSOL Multiphysics. Spatial dimension was 3D, physics was heat transfer (solid), and study type was steady analysis.

In this study, thermal analysis was performed on four types of models. Fig. 1 shows the model of the SiO₂ 1DPhC resonator used in the simulation. In this way, the model is placed in the center of a cube containing gas. All faces of the cube were constant at 300K, and the initial temperature was uniformly set at 300K. These conditions are the same for other models.

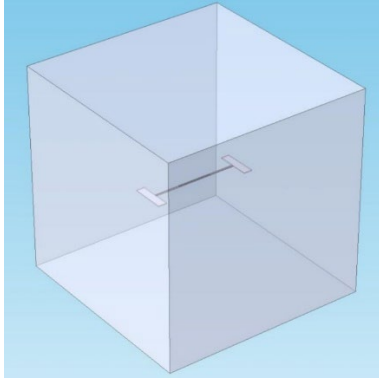


Fig. 1: Simulation model (SiO2 1D PhC)

Fig. 2 shows the Si 1D PhC resonator model in (a), the Si 2D PhC resonator model in (b), the SiO2 toroid resonator model in (c), and the SiO2 1D PhC resonator model in (d). 2D PhC has a pore spacing of 420 nm, a pore radius of 115.5 nm, and a slab thickness of 210 nm. In addition, the cavities on both sides of the region that traps light have their radii reduced to 63 nm and shifted outward by 32 nm from their original positions.^[6] The base material of the SiO2 toroid is silicon, and the upper material is silica.

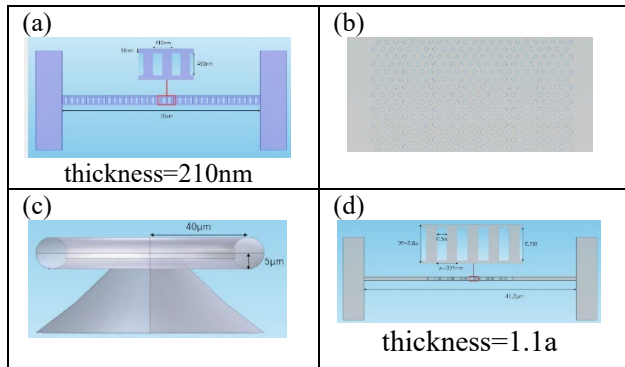


Fig. 2: (a) Si 1D PhC resonator's model モデル. (b) Si 2D PhC resonator's model. (c) SiO2 toroid resonator's model. (d) SiO2 1D PhC resonator's model.

In this study, we continued to inject light into the resonator and measured the temperature of the resonator after reaching a steady state. The gas in the cube was set to a mixed gas of hydrogen and air, and thermal analysis was performed in the range of hydrogen concentration of 0 to 100%.

4.Result

Fig. 3 shows the temperature distribution of each resonator in the steady state when the hydrogen concentration is 0%.

(a) is the temperature distribution of the Si 1D PhC resonator, (b) is the temperature distribution of the Si 2D PhC resonator, (c) is the temperature distribution of the SiO2 toroid resonator, and (d) is the temperature distribution of the SiO2 1D PhC resonator. (b) is a side view.

Since heat is also transferred to the air, it can be seen that the thermal conductivity of the surrounding gas also affects the temperature distribution of the resonator.

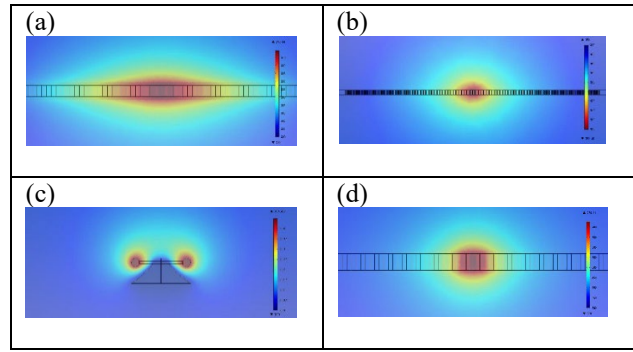


Fig. 3: Temperature distribution (a) Si 1D PhC resonator, (b) Si 2D PhC resonator, (c) SiO2 toroid resonator, (d) SiO2 1D PhC resonator.

Fig. 4 shows a graph normalized by dividing the relationship between the amount of change in the resonance wavelength and the hydrogen concentration by the line width of the resonance wavelength of each resonator. (a) shows a figure with a hydrogen concentration range of 0 to 100%, and (b) shows a figure with a hydrogen concentration range of 0 to 10%. The power of the input light was set for each resonator so that the amount of change at 100% hydrogen concentration was about 250.

It is assumed that a half-value and half-width wavelength shift can be detected.^[6] In this case, the amount of change in hydrogen concentration when the amount of shift with respect to the line width changes by 0.5 is the resolution of the sensor, and the steeper the graph, the higher the sensor sensitivity. Therefore, it can be seen that the sensitivity of the resonator made of silica is high under low concentration. When the hydrogen concentration is 5% or less, the SiO2 toroid resonator has a resolution of 0.063%, and the SiO2 1D PhC resonator has a resolution of 0.062%.

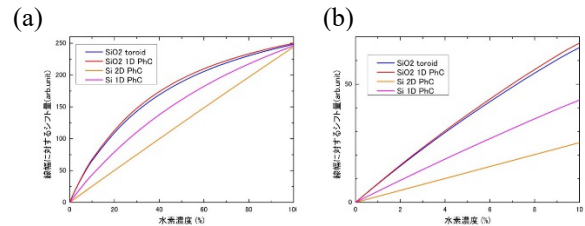


Fig. 4: Hydrogen concentration – $\frac{\Delta\lambda}{\delta\lambda}$
Hydrogen concentration's range (a) 1~100% (b) 1~10%

Fig. 5 shows the relationship between the amount of shift of the resonance wavelength with respect to the line width and the hydrogen concentration when the input light is 0.02mW. In (a), the figure with the hydrogen concentration range set to 0 to 100% is shown, in (b), the figure with the hydrogen concentration range set to 0 to 10% is shown.

From Fig. 5, it can be seen that the Si 1D PhC resonator has a sensitivity 10^4 or more higher than that of other resonators. When the hydrogen concentration is 5% or less, the resolution is 0.13%. This is thought to be due to the higher two-photon absorption efficiency than the linear absorption efficiency. Also, the reason why there is a large difference between Si 2D PhC and Si 1D PhC is that the surface area of the one-dimensional crystal is

larger than that of the two-dimensional crystal and it is easily affected by gas.

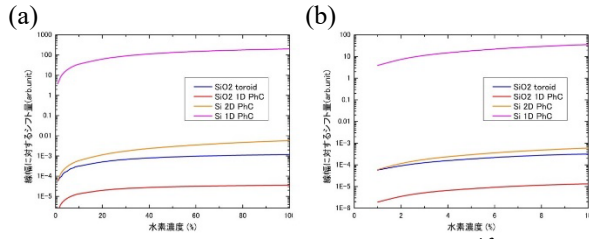


Fig. 5: Hydrogen concentration – $\frac{\Delta\lambda}{\lambda}$
Hydrogen concentration's range (a) 1~100% (b) 1~10%
($P_{in} = 0.02mW$)

5.Conclusion

Aiming at the realization of a hydrogen sensor using a micro-optical resonator, thermal analysis was performed on four types of models: silica toroid resonator, silica 1DPhC resonator, silicon 1DPhC resonator, and silicon 2DPhC resonator.

From the simulation results, it was found that the resonator made of silica is superior to the sensor sensitivity under low concentration when the power consumption is not considered, but the silicon 1DPhC resonator is superior when the power consumption is considered. Silicon 1DPhC can detect a change in hydrogen concentration of 0.13% when the power of the input light is 0.02mW.

参考文献

- [1] T. Hübert, L. Boon-Brett, G. Black and U. Banach, "Hydrogen sensors – A review," *Sensors and Actuators B: Chemical* **157** (2), pp. 329, 2011.
- [2] Xiangyi Xu, Weijian Chen, Guangming Zhao, Yihang Li, Chenyang Lu and Lan Yang, "Wireless whispering-gallery-mode sensor for thermal sensing and aerial mapping," *Light: Science & Applications* **7** (62), 2018.
- [3] Tal Carmon, Lan Yang, and Kerry J. Vahala, "Dynamical thermal behavior and thermal self-stability of microcavities," *Opt. Express* **12**, pp. 4742-4750, 2004.
- [4] Yuki Taguchi, Yasushi Takahashi, Yoshiya Sato, Takashi Asano, and Susumu Noda, "Statistical studies of photonic heterostructure nanocavities with an average Q factor of three million," *Opt. Express* **19**, pp. 11916-11921, 2011
- [5] Fushimi A, Taniyama H, Kuramochi E, Notomi M, Tanabe T, "Fast calculation of the quality factor for two-dimensional photonic crystal slab nanocavities," *Opt Express*. 22 (19), pp. 23349-23359, 2014 Sep 22.
- [6] Nebiyu A. Yebo, Petra Lommens, Zeger Hens, and Roel Baets, "An integrated optic ethanol vapor sensor based on a silicon-on-insulator microring resonator coated with a porous ZnO film," *Opt. Express* **18**, pp. 11859-11866, 2010.

appendix

A simulation was performed on the performance of a polystyrene-based microsphere optical resonator (Polystyrene sphere) as a hydrogen gas sensor. Fig. 6 shows the model and heat source of the microsphere optical resonator. Fig. 6 shows the bluish part. It was used as a heat source.

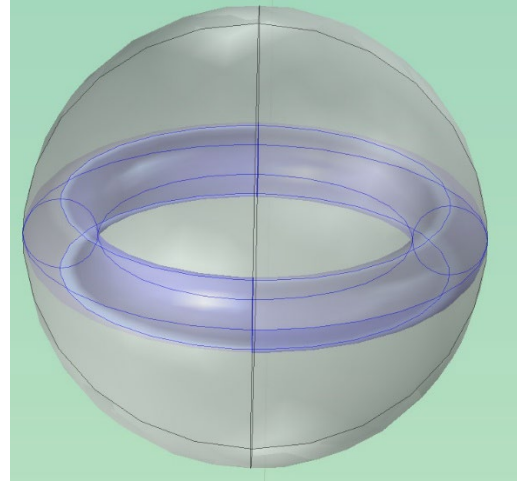


Fig. 6: microsphere resonator

Fig. 7 shows the results when the calorific value was set so that the resonance wavelength shift amount with respect to the line width at 100% hydrogen concentration was about 250. (a) shows the figure with the hydrogen concentration range set to 0 to 100%, (b) shows the figure with the hydrogen concentration range set to 0 to 10%. From Fig. 7, it can be seen that the microsphere optical resonator has the best sensitivity under low concentration. At this time, the resolution is 0.032% when the hydrogen concentration is 5% or less. The reason for the high sensitivity at low concentrations is considered that the thermal conductivity of polystyrene is between air and hydrogen, so when there is no hydrogen in the surroundings, heat is preferentially transferred to the resonator rather than the surrounding gas, but when there is hydrogen in the surroundings, heat is preferentially transferred to the surrounding gas rather than in the resonator.

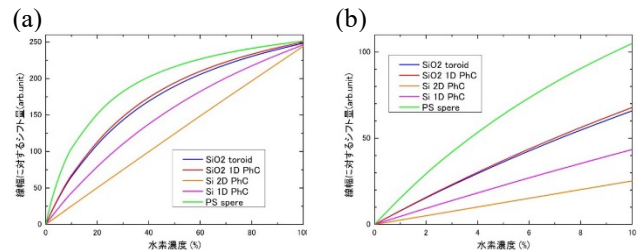


Fig. 7: Hydrogen concentration – $\frac{\Delta\lambda}{\lambda}$
Hydrogen concentration's range (a) 1~100% (b) 1~10%

Design and optical measurement of SiN microresonators for soliton comb generation

Atsushi Takano (B4)

Microcombs are generated by efficiently causing four-light wave mixing by confining light using a micro-optical resonator. Furthermore, phase-synchronized soliton comb is generated by precise control of detuning (difference between pump light and resonance frequency). In this study, we examined the design of a SiN ring resonator capable of generating Soliton comb and measured it optically.

Key words: Microresonator, Microcomb, Soliton comb, SiN(Silicon Nitride)

1. Introduction

Optical resonators are devices that confine and accumulate light at a specific resonance frequency. It is considered as an optical transmission system incorporating feedback, and light goes round while reflecting repeatedly in the system without leaking out.

The WGM (Whispering Gallery Mode) resonator has a circular structure, and the light wave that satisfies the wavelength λ represented by equation (1) is trapped.

$$2\pi R = \lambda \cdot l \quad (l = 1, 2, 3, \dots) \quad (1)$$

The Free spectral range (FSR) which represents the frequency interval between adjacent modes of the WGM resonator using a material with a refractive index n , can be expressed as follows.

$$\text{FSR} = \frac{c}{2\pi R} \quad (2)$$

In the case of a microresonator, it can easily produce FSRs in the order of GHz and THz because they have a very small radius R . There is a Q value as a value which represents the performance of confining the light of the resonator. The Q value is defined as follows.

$$Q = \omega_0 \frac{\text{Energy stored in the resonator}}{\text{Energy to be lost per unit time}} \quad (3)$$

Optical frequency comb is light with a spectrum equal to each other in the frequency domain and is a pulse in the time domain.

There are methods for generating optical frequency combs, such as a mode-locked laser such as a titanium sapphire laser and a fiber laser, and a method using an electro-optical modulator. In 2007, optical frequency combs using micro-optical resonators were announced, and they came to be called microcombs.

Dispersion design is important for the generation of microcombs. When dispersion is not taken into account, the interval between the resonance modes is constant, but since the actual

resonator has dispersion, FSR has a wavelength dependence. The generation of microcombs basically requires abnormal dispersion.

Phase-synchronized soliton comb is realized when two are balanced: pulse expansion by abnormal dispersion characteristics of the resonator, balance of pulse shape by pulse compression by self-phase modulation, and power balance due to loss in parametric gain and resonator.

2. Microresonator

Types of microresonators include crystal resonators that manually scrape rods such as MgF_2 and CaF_2 to form resonators, and silica toroid resonators [1] that can be reflowed with a CO_2 laser by etching a silica base.

In this study, we use a SiN (silicon nitride) microresonator. Chip integration is possible using CMOS process, although the Q value of the SiN resonator is lower than that of MgF_2 -crystal ($\sim 10^9$) and silica toroids ($\sim 10^8$). It is now an indispensable material for photonics because of its small loss in the communication wavelength band and large nonlinearity [2].

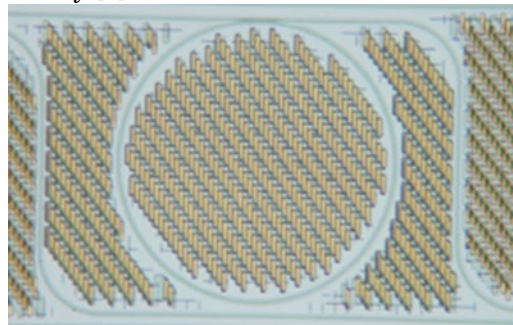


Fig.1: SEM image of SiN ring resonator

The production of SiN ring resonators was commissioned by a founder called Ligentc MPW run. This is because when the SiN layer is created on a Si substrate into a SiN film, spontaneous crack generation is remarkably observed from the difference in coefficient of thermal expansion, and it is very difficult to fabricate.

The coupling changes depending on the size of

the gap (distance between the resonator and the bus waveguide) of the SiN ring resonator.

2. Measurement procedure

Fig. 2 shows the measurement setup. A light of -10 dBm from a wavelength variable laser is input to a resonator integrated on a chip, and the output light intensity is measured with a power meter. The wavelength is swept from 1550 nm to 1600 nm at a speed of 6 nm/s, and the transmission spectrum as shown in Fig. 3(a) can be obtained when the wavelength and power data are centrally managed by DAQ. The rod extending below the obtained transmission spectrum is called a dip, and when enlarged, it becomes like Fig. 3(b). Lorenz fitting was performed for this dip, and Q value is obtained by substituting the half-width $\Delta\lambda$ and the resonant wavelength λ_0 in equation (4).

$$Q_{\text{load}} = \frac{\Delta\lambda}{\lambda_0} \quad (4)$$

Here, Q_{load} is a Q value obtained by measurement, including absorption by the material and coupling loss with the waveguide.

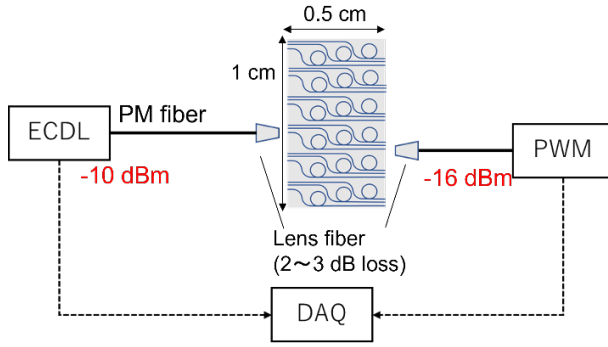


Fig.2: Measurement setup

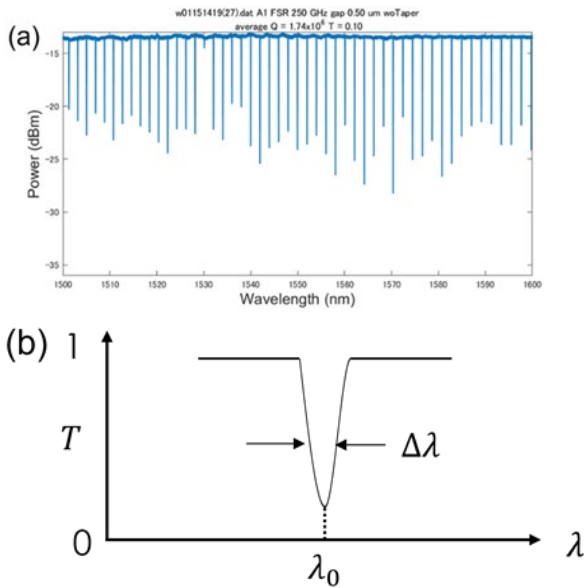


Fig.3: (a) Transmittance Spectrum (b) Illustration of Lorenz fitting

The peak spacing of the transmission spectrum

coincides with the FSR when there is no dispersion. Since the peak interval shifts little by little when there is dispersion, the dispersion can be obtained by fitting this deviation with a quadratic function.

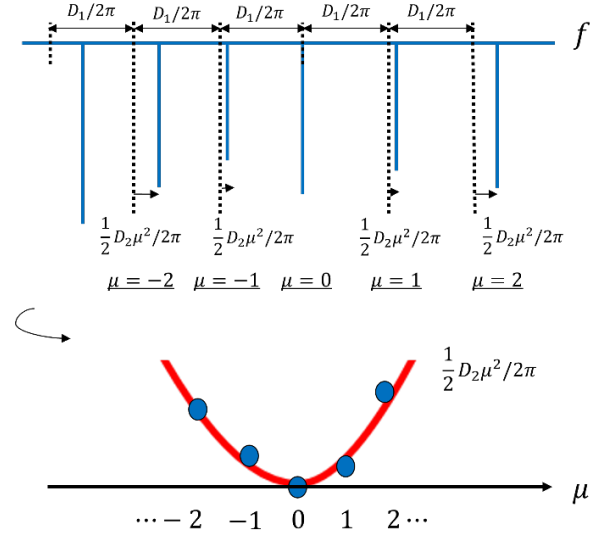
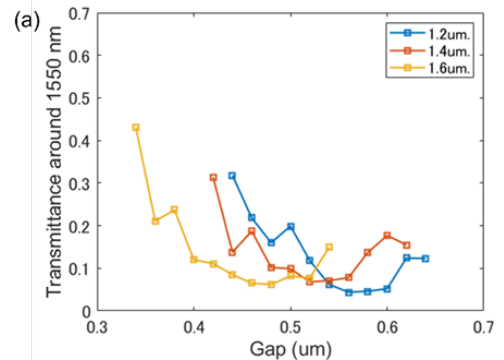


Fig.4: Dispersion Measurement

4. Measurement Result

Fig. 5 shows the results of optical measurements of chips fabricated in 2021. (a) is the measurement result of transmittance and (b) is the measurement result of Q value. The FSR was 250 GHz, and the ring waveguide width was 1.6 μm , and the bus waveguide width and gap were given values.

When comparing the Q value with the transmittance, it can be seen that the Q value is the highest when approaching the undercoupling with a slightly larger gap from the critical coupling, which is the coupling state with the lowest transmittance. Since soliton comb generation requires high Q value and low transmittance, it is necessary to design a resonator to include a part that is somewhat closer to the undercoupling from the critical coupling. Regarding the bus waveguide width, based on the fact that the Q value in the gap approaching the under coupling from the critical is higher than the other, and that the ring waveguide and the bus waveguide are the same in the previous research, the bus waveguide is fixed to 1.6 μm in the design.



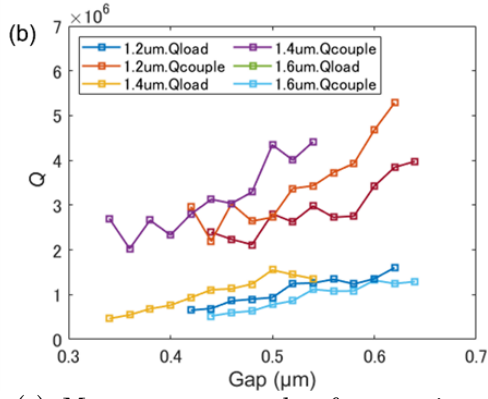


Fig.5: (a) Measurement result of transmittance (b) Measurement result of Q value

Based on the evaluation results of the chip in 2021, the bus waveguide width was examined for the design of the chip made in 2022. The bus waveguide width was 1.6 μm , and this time we decided to evaluate the influence of the ring waveguide width. Fig. 6 shows the measurement results.

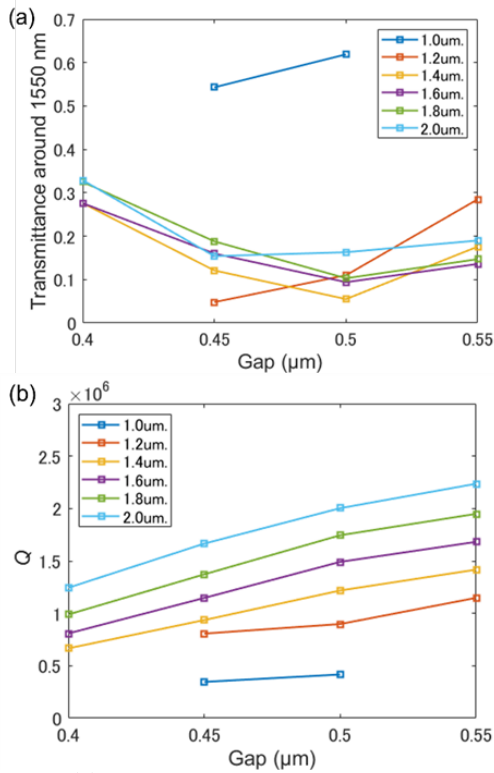


Fig.6: (a) Measurement result of transmittance (b) Measurement result of Q value

As with the measurement results of the 2021 chip, it became a critical coupling with a gap of 0.5 μm . From Fig. 6(b), the Q value seems to increase with increasing ring waveguide width, which seems to be due to an increase in the actual gap.

Finally, fig. 7 shows the dispersion measurement results of a resonator with a ring waveguide width of 1.2 μm at 250 GHz of FSR contained in chip A1 manufactured in 2022.

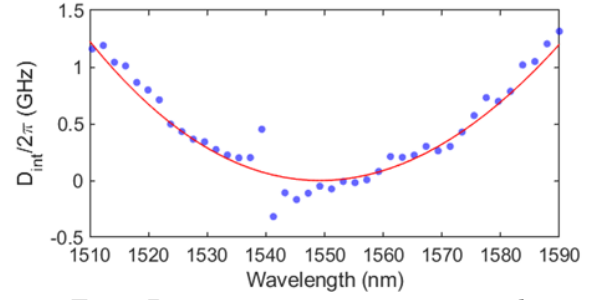


Fig.7: Dispersion measurement results

The dispersion could be determined as $D=81.0$ ps/km/nm, and the theoretical value $D=83.6$ ps/km/nm was close. This is an abnormal dispersion, and it is suitable for the generation of soliton comb. However, there is a mode coupling at 1540 nm, which may inhibit the development of soliton comb.

5.Conclusion

By examining the relationship between the gap and coupling of SiN ring resonators, we found the optimal gap for the generation of soliton comb and found that the optimal gap matches if it is a resonator of the same design. It was found from the dispersion measurement that it had anomalous dispersion close to the theoretical value. Some resonators showed mode coupling.

References

- [1] P. Del' Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth and T. J. Kippenberg, "Optical frequency comb generation from a monolithic microresonator." *Nature* **450**, 1214–1217 (2007).
- [2] Ikeda, K., Saperstein, R. E., Alic, N. and Fainman, Y., "Thermal and Kerr non linear properties of plasma-deposited silicon nitride/silicon dioxide waveguides." *Opt. Express* **16**, 12987–12994 (2008).

Low loss SiN ring resonators deposited by Hot-wire CVD method

Shota Sota (M2)

In this study, I have investigated the low-loss ring resonators fabricated using SiN deposited by a low-temperature deposition method, Hot-Wire CVD, and achieved a Q factor exceeding 5.0×10^5 in the C-band band, where the absorption loss of hydrogen-bonded groups is large. Finally, I observed the generation of microcomb.

Key words: Optical microresonator, Microcomb, Silicon nitride

1. Background

Silicon nitride (SiN) has a wide band gap and is transparent over a very wide wavelength range (470 nm to 6.7 μm), so it is not affected by two photon absorption in the communication wavelength range, can be fabricated using semiconductor CMOS processes (CMOS compatibility), and approximately 50 times that of optical fiber (silica) in the telecommunication wavelength band [1], it is a material that has attracted considerable attention as a platform for microcomb generation. However, SiN has normal dispersion in the optical communication bandwidth, so a film thickness of 700 nm or more with SiO₂ cladding is required to obtain an anomalous dispersion in order to generate microcomb. This causes high tensile stress, which in turn lowers yields rate. In addition, although a deposition temperature below 400 °C is desirable for future integration, the low-temperature deposition method suffers from the absorption losses in the infrared vibrational modes due to residual N-H (~3400 cm⁻¹) and Si-H bonding groups (~2200 cm⁻¹) in the film [2]. In this report, we fabricated a ring resonator using thick SiN film (~750 nm) deposited by hot-wire CVD method and evaluated its optical properties.

2. Basic Fabrication Method

SiN with a refractive index of ~2.02 (632.8 nm) and a thickness of 750 nm was deposited on a Si substrate with a thermal oxide film with following condition: SiH₄: 2.1 sccm, NH₃: 80 sccm, pressure 4 Pa, substrate temperature 400°C, tungsten wire power input 600 W and deposition rate 5.6 nm/min. Then, negative resist was coated, patterns were drawn by EB lithography, then dry etching was performed (CHF₃/Ar for 30s followed by SF₆/O₂ for about 5min30s), and 2 μm of silica was deposited as the over-cladding layer.

3. Study for reducing losses

(1) Reduction of micromasks

As shown in Figure 1(a), micromasks exist near the waveguide and may be a source of light scattering loss. These micromasks are thought to be caused by resist that collapsed and scattered during development. Therefore, (i) oxygen plasma ashing before etching and (ii) increasing the EB base dose and decreasing the resist bake temperature were performed to reduce the micromasks, respectively. Figure 1(b) (i) shows that ashing decreases the Q

factor. This may be due to the increased wettability (hydrophilicity) of the resist surface during the ashing process, resulting in a larger than usual amount of H₂O adhering to the resist, which increases the amount of reaction byproducts in the first stage of DE (CHF₃/Ar etching), resulting in an increase in pattern surface and sidewall roughness. Figure 1(b)(ii) shows that the Q factor of the longer wavelength side has improved. The reason for this is that increasing the base dose during EB writing increases the charge of the electron beam irradiating the resist, which increases the time required for photosensitization and development, thereby eliminating erosion of the topmost surface, and the lowering the bake temperature occur that the less likely molecular cross-links are formed and the less non-uniformity in the resist, which results in less micromasks. This is thought to be due to a decrease in the number of micromasks.

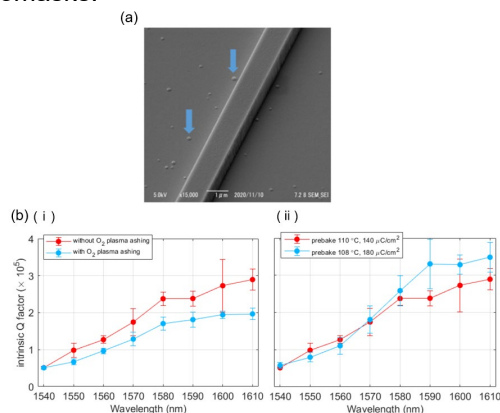


Figure1 : (a) SEM images of SiN waveguide. Arrows in images show parts of lumps and micromasks. (b) Average intrinsic Q factor from 1540 to 1610 nm introducing process (i) or (ii).

(2) Surface Roughness Reduction

We investigated the possibility of reducing the surface roughness of SiN waveguides and improving the Q factor by introducing CMP (Chemical Mechanical Polishing) polishing. The Q factor data in Figure 2(a) shows that the Q factor remained almost the same, with only a slight decrease due to manufacturing errors. The surface roughness was measured by AFM (Atomic Force Microscope) (Figure 2(b)), and the Q factor by surface roughness was calculated as shown in Table 1. This result indicates that surface roughness is not a source of suppression of the current Q factor.

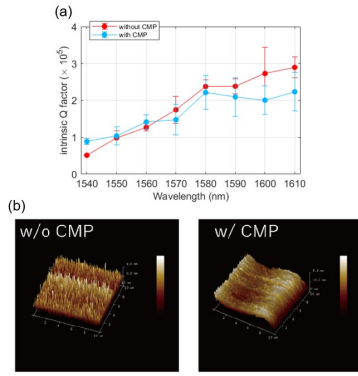


Figure2 : (a) Average intrinsic Q factor from 1540 to 1610 nm introducing CMP. (b) AFM image.

Table1 : Q factor by surface roughness with and without polishing

Sample	RMS (σ (nm))	Correlation length (L_c (μ m))	Loss (dB/cm)	Q factor
without CMP	0.8875	0.2893	0.25	1.5×10^6
With CMP	1.158	24.13	0.015	2.5×10^7

(3) Reduction of residual hydrogen bonding groups

Since the above results showed no particular change in the Q factor at short wavelengths, absorption loss due to residual hydrogen bonding groups in the film was considered to be dominant. Therefore, after etching, annealing was performed at 1050°C in a nitrogen environment. The Q factor for each annealing time are shown in Figure 3. The results show that the absorption by the hydrogen bonding group is sufficiently reduced in 3 hours, because the Q factor does not differ depending on the wavelength. Q factor exceeding 105 were obtained.

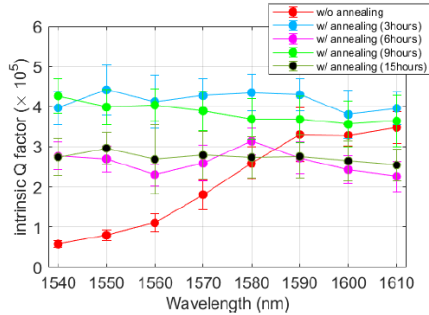


Figure3 : Average Intrinsic Q factor from 1540 to 1610 nm introducing annealing.

4. conclusions and future prospects

An optical ring resonator was fabricated using a thick SiN film (750 nm) deposited by Hot-wire CVD in a CMOS-compatible process. FSR ~ 400 GHz and $Q_{int} > 5 \times 10^5$ were observed in the optical communication wavelength band. Microcomb generation was also observed using the fabricated resonator (Figure 4). At 100 mW input, (a) a primary comb state was observed, and at >500 mW input, (b) a flat-top MI comb state was observed.

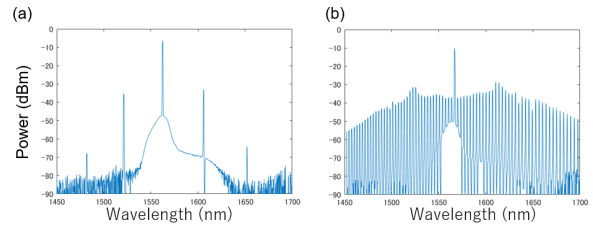


Figure4 : Microcomb with (a) 100 mW pumping, (b) 500 mW pumping.

Based on [3], it is concluded that the anomalous dispersion of the group velocity dispersion relative to the Q factor is insufficient to determine whether solitoncomb can be generated in this resonator. Therefore, future prospects include dry etching optimization to reduce the roughness of the waveguide sidewalls to further improve the resonator Q factor, optimization of the EB base dose amount and resist bake temperature to further reduce the micromasks, and optimization of the over-cladding layer deposition to reduce air bubbles between the ring and the waveguide. It is believed to be necessary. It is concluded that apart from improving the Q factor, it is necessary to optimize the composition ratio of the SiN film during deposition or change the ring shape to achieve stronger anomalous dispersion in the resonator.

References

- [1] M. H. P. Pfeiffer, C. Herkommer, J. Liu, T. Morais, M. Zervas, M. Geiselmann, and T. J. Kippenberg, *IEEE Journal of Selected Topics in Quantum Electronics* 24, 1–11 (2018).
- [2] W. A. Lanford, and M. J. Rand, *J. Appl. Phys.* **49**, 2474-2477 (1978).
- [3] Shun Fujii, Shuya Tanaka, Tamiki Ohtsuka, Soma Kogure, Koshiro Wada, Hajime Kumazaki, Shun Tasaka, Yosuke Hashimoto, Yuta Kobayashi, Tomohiro Araki, Kentaro Furusawa, Norihiko Sekine, Satoki Kawanishi and Takasumi Tanabe, *Opt. Express* 30, 1351-1364 (2022)

Investigation of control operation for automated generation of a dissipative Kerr soliton with FPGA

Shuto Sugawara (M1), Hajime Kumazaki

A dissipative Kerr soliton has been reported in a variety of studies due to its stability and wide bandwidth. A dissipative Kerr soliton should be easily generated for efficient application experiments. In this report, we describe our investigation of FPGA operation with the goal of automating the generation of a dissipative Kerr soliton with FPGA to ease the generation of dissipative Kerr soliton.

Key words: FPGA, Dissipative Kerr soliton, Microresonator

1. Introduction

A dissipative Kerr soliton in a microresonator (soliton microcomb) [1] has various excellent characteristics, including high stability such as phase locking, wide bandwidth, and high repetition rate due to the small size of the resonator. These characteristics have led to a wide variety of possible applications, including wavelength-division multiplexing [2] and light sources for LiDAR [3]. However, because the power inside the resonator decreases at the moment that the soliton microcomb is generated, the resonator cools down rapidly and the soliton microcomb disappears. Because of this characteristic, the stable generation of a soliton microcomb requires a prescribed procedure to compensate for the intracavity power. The generation procedure can be divided into two main steps. The two processes are the soliton microcomb generation and stabilization of the generated comb. Several methods for generating a soliton microcomb have been considered. Typical methods for generating soliton combs include a method called fast-scan, which suppresses the temperature variation of the resonator until the soliton microcomb is generated by quickly sweeping the wavelength of the pump light [1], and a method using two lasers to compensate for the intracavity power variation during a soliton microcomb generation [4]. In our laboratory, we mainly use the fast-scan method to a soliton microcomb. A soliton microcomb quickly disappears if the detuning, which represents the difference between the wavelength of the pump light and the resonance frequency, fluctuates too much, so stabilization of the detuning is necessary after the soliton microcomb is generated. Detuning stabilization is achieved using the Pound-Drever-Hall (PDH) technique [5]. A schematic diagram of a soliton microcomb generation is shown in Fig. 1.

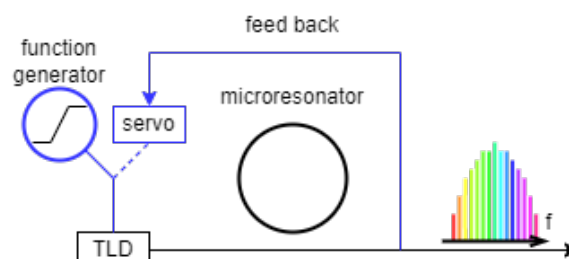


Fig. 1 Schematic diagram of soliton comb generation. First, the laser is swept by a function generator, and then the signal is switched and stabilized. TLD: tunable laser diode.

Our current issue is that the generation and stabilization are performed separately. This requires manual linking of each operation. In other words, the soliton microcomb occurs, and stabilization must be performed before the soliton microcomb disappears. This method requires time and effort to generate the targeted soliton microcomb. The goal is to automate the two processes with a field-programmable gate array (FPGA), a digital circuit chip that can be freely designed. By integrating the signal generator and controller into a single device, it is possible to automatically detect the occurrence of a soliton microcomb and immediately shift to a stabilized state, thereby reducing the time and effort required for soliton microcomb generation.

2. FPGA device

In this study, we used a device named STEMLab 125-14, which is manufactured by redpitaya. Since an FPGA is a digital circuit, an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC) are required for the analog inputs and outputs needed for feedback control. STEMLab 125-14 has a DAC and ADC on the same board as the FPGA and can be used as an analog controller immediately. The chip is a Xilinx Zynq 7010. The ADC is LTC2145-14 from Analog devices. The ADC has two channels with a voltage range of ± 1 V and a resolution of 14 bits. The DAC is AD 9767 from Analog devices. It also has two channels with a voltage range of ± 1 V and a resolution of 14 bits.

3. Operation check

To verify the operation of the board, sin waves were output using the software supplied with STEMLab 125-14. The output waveforms are shown in Fig. 2. Although only channel 1 was used for output, it was confirmed that a similar waveform as output from channel 2, indicated that there was crosstalk between the two channels. This crosstalk is large enough to distort both waveforms when output simultaneously, effectively limiting the number of usable channels to one on this board.

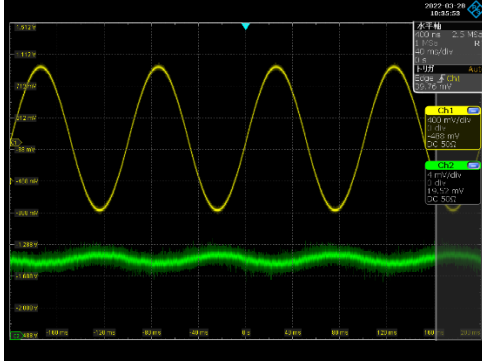


Fig. 2 Output waveform of STEMLab-125-14. Yellow and green waveforms represent the output waveforms of channel 1 and channel 2, respectively.

4. PID control

The setup is shown in Fig. 3 (a) was used to verify the operation of PID control with FPGA. The PID control program used was PyrPL, an open-source project [6]. The software provides many functions such as oscilloscope, network analyzer, and feedback control. As a control check, an external input signal and the output of the FPGA were combined by an additive circuit and used as an error signal. The error signal as the controlled target was checked by inputting a step function to the input to seed how the error signal fluctuates. The parameters in the PID control are: $P = -24(/1024)$, $I = -53 (64 \mu s)$, $D = -57 (7.5 ns)$. The measurement results are shown in Figs. 3 (b) and (c). When the control is turned off, the error signal moves in the same manner as the input signal, but when the control is turned on, the error signal moves to a constant value, confirming feedback control.

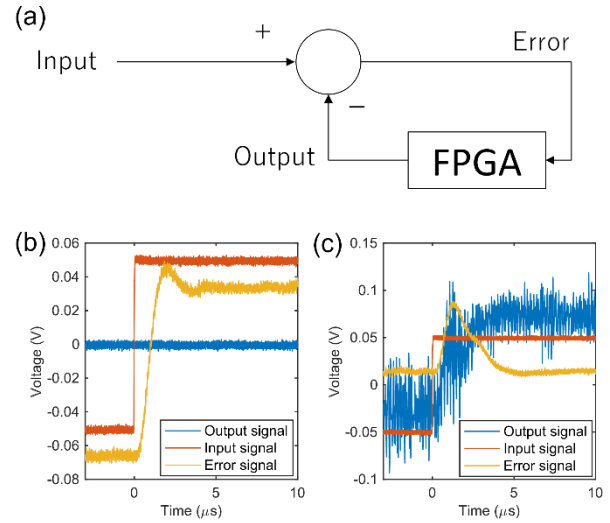


Fig. 3 (a) Schematic diagram of PID control operation check. (b) The behavior of each signal without feedback control. (c) The behavior of each signal with feedback control.

References

- [1] T. Herr, V. Brasch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, *Nature Photonics* **8**, 145–152 (2014).
- [2] P. Marin-Palomo, J. N. Kemal, M. Karpov, A. Kordts, J. Pfeifle, M. H. P. Pfeiffer, P. Trocha, S. Wolf, V. Brasch, M. H. Anderson, R. Rosenberger, K. Vijayan, W. Freude, T. J. Kippenberg, and C. Koos, *Nature* **546**, 274–279 (2017).
- [3] P. Trocha, M. Karpov, D. Ganin, M. H. P. Pfeiffer, A. Kordts, S. Wolf, J. Krockenberger, P. Marin-Palomo, C. Weimann, S. Randel, W. Freude, T. J. Kippenberg, and C. Koos, *Science* **359**, 887–891 (2018).
- [4] S. Zhang, J. M. Silver, L. Del Bino, F. Copie, M. T. M. Woodley, G. N. Ghalanos, A. Ø. Svela, N. Moroney, and P. Del’Haye, *Optica* **6**, 206 (2019).
- [5] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, *Appl. Phys. B* **31**, 97–105 (1983).
- [6] L. Neuhaus and S. Deleglise, <https://pyrpl.readthedocs.io/en/latest/>.

Coupling of Si Waveguide and SiN Waveguide with Inverse Tapered Structure

Ryo Nishihata (B4)

In order to implement Si optical integrated circuits with SiN microresonators, it is essential to bond an optical frequency comb light source and a chip made of different materials. It is difficult to conduct an optical frequency comb light source with sufficiently high efficiency using existing bonding methods. In this study, the inverse tapered structure that enables highly efficient propagation of optical frequency comb is investigated as a method of coupling dissimilar materials, and at the same time, a comparative study of analytical methods for micro waveguides is conducted.

Keywords: Si waveguide, SiN waveguide, inverse tapered structure, BPM, FEM, FDTD

1. Background

In silicon photonics, silicon nitride (SiN) based microresonators are currently attracting attention as an optical frequency comb light source. When using these microresonators as an optical frequency comb light source, it is necessary to couple SiN waveguides and Si waveguides on an optical integrated circuit. Without appropriate structure, the coupling efficiency is not enough to be practical. Therefore, efficient structures must be used when coupling waveguides. Some bonding methods such as photonic wire bonding (PWD)^[1] and multilayer^[2] already exist. However, they are not suitable for use in optical integrated circuits with SiN microresonators due to the high power of the optical frequency comb and the thickness of the waveguide. Therefore, we investigated an inverse tapered structure, in which the mode shape and effective index of the guided light can be manipulated by using a tapered structure in which the waveguide width gradually narrows to increase the junction efficiency (Fig. 1). Inverse tapered structures are easy to fabricate due to their relatively simple structure and can be used in Si optical integrated circuits with SiN microresonators.

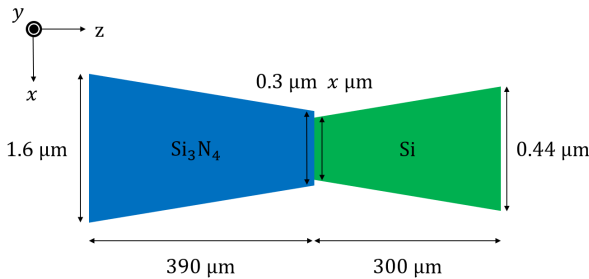


Fig. 1. Inverse tapered structure used in the simulation.
(SiN thickness: 0.8 μm , Si thickness: 0.22 μm)

2. Simulation

In this study, simulations were performed for modal analysis of waveguide and light propagation analysis. The mode shape and effective index of a waveguide can be determined using Maxwell's equations and boundary conditions, but mathematical solutions cannot be obtained. For this reason, various methods exist for obtaining approximate solutions. In the simulations, the three-layer slab approximation and finite element method (FEM) were used for the modal analysis of the waveguide, and Finite-difference time-domain (FDTD) method was used for the

light propagation analysis.

MATLAB was used for the three-layer slab approximation, and Rsoft was used for the FEM and FDTD methods. In the modal analysis, the effective index and TE₀ mode shapes were obtained for different waveguide widths. In the simulation of light propagation, the coupling efficiency was obtained for different Si waveguide widths at the coupling part using the model shown in Fig. 1. Because the FDTD method is computationally expensive, a region $\pm 10 \mu\text{m}$ away from the junction in the z direction was used as the simulation region, and the TE₀ mode obtained from the FEM was used as the incident light.

3. Result

Fig. 2 shows the effective index as a function of Si/SiN waveguide width calculated from the three-layer slab approximation and FEM.

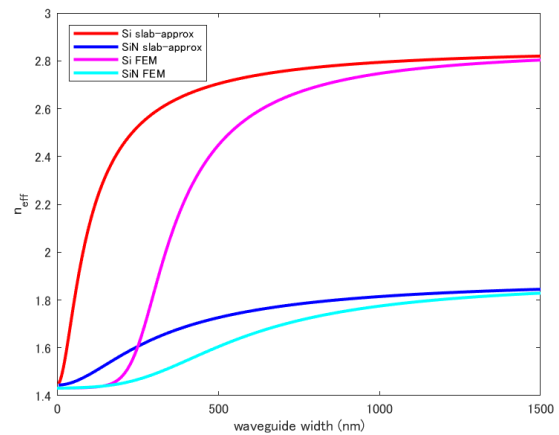


Fig. 2. The effective index as a function of Si/SiN waveguide width

Fig. 3 shows the coupling efficiency obtained using the FDTD method, the mode overlap obtained using FEM, and the effective index of the Si/SiN waveguide obtained using FEM as a function of the Si waveguide width. The coupling efficiency reached a maximum value of 0.967 when the Si waveguide width was 200 nm.

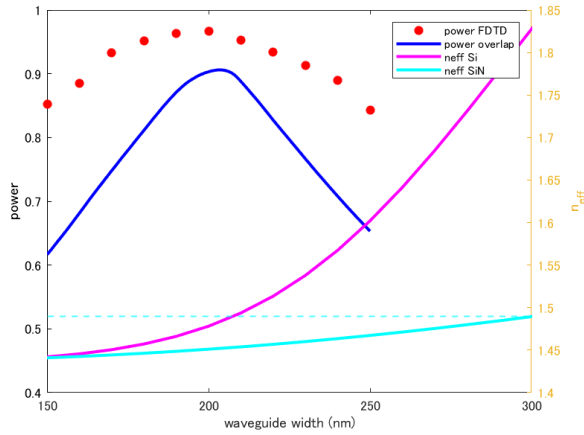


Fig. 3. Coupling efficiency, mode overlap and effective index as a function of waveguide width (FDTD, FEM).

Fig. 4 shows the pointing vectors of the TE fundamental mode at the waveguide obtained using FEM.

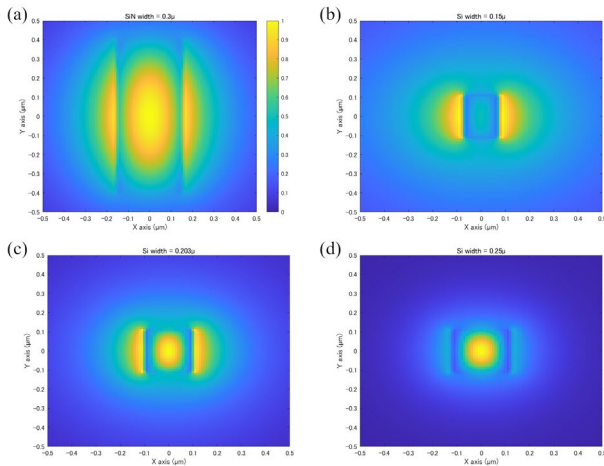


Fig. 4. The pointing vectors of the TE fundamental mode (a). SiN width (300 nm), (b). Si width(150 nm), (c). Si width(203 nm), (d). Si width(250 nm)

4. Discussion

In Fig. 2, the effective indexes obtained by the three-layer slab approximation are the same as those obtained by FEM in the region where the waveguide width is wide, but the results are significantly different in the region where the waveguide width is less than 1 μm . The main reason for this is that the three-layer slab approximation assumes that light is sufficiently confined within the waveguide to calculate the modes, but when the waveguide width is narrow, the fundamental modes exist mainly outside of the waveguide (Fig. 4), so the assumption is not satisfied.

In Fig. 3, the Si waveguide widths for the case of maximum coupling efficiency, maximum overlap of the fundamental modes at the coupling plane, and matching effective index at the coupling plane are nearly identical. The mode shapes and effective indexes are affected by the index of the waveguide, but when the waveguide width is narrow, the modes are mainly located outside of the waveguide (clad layer) (Fig. 4). Since the cladding of the waveguides joined in this study are both SiO_2 and the index of clad layer does not change, the cases in which the effective index matches and the mode overlap is maximized coincide, and as a

result, the cases in which the light propagation efficiency is maximized also match.

The coupling efficiency obtained by the FDTD method was always higher than the mode overlap analyzed by FEM. This difference indicates that the light coupling in the inverse tapered structure is not limited to light with overlapping modes at the coupling faces. This is because the modes of the waveguide change as the Si waveguide width becomes wider in the inverse tapered structure, and light that exists outside of the modes of the waveguide at the coupling face recombines with the mode of waveguide.

5. Conclusion

The results for the effective index and the shape of modes indicate that the three-layer slab approximation is not suitable for the analysis of micro waveguides where the modes also exist outside of the waveguide.

When the waveguide width is narrow, the cases where the effective refractive index matches and the mode overlap is maximal are very close, and as a result, the structure with maximal coupling efficiency is also close to them.

Simulations of light propagation in the inverse-tapered structure show that light seeping out of the waveguide at the junction plane is recombined during wave propagation.

Therefore, when analyzing the junction of micro waveguides, it was thought that efficient and accurate results could be obtained by using FEM to determine the structure that matches the effective index and mode shape at the coupling surface firstly, then using the FDTD method to determine the structure that maximizes the coupling efficiency.

References

- [1] N. Lindenmann, *et. al.*, “Connecting Silicon Photonic Circuits to Multicore Fibers by Photonic Wire Bonding”. *J. Light. Technol.* **33**, 755-760 (2014).
- [2] W. D. Sacher, *et. al.*, “Tri-layer silicon nitride-on-silicon photonic platform for ultra-low-loss crossings and interlayer transitions”, *Opt. Express* **25**, 30862-30875 (2017)

Dissipative Kerr solitons for time division multiplexing communications.

Koya Tanikawa (B4) Shun Tasaka (M2) Satoki Kawanishi

Microcombs generated by microresonators are expected to be applied to various field. Dissipative Kerr solitons (DKS), which are mode-synchronized microcombs, are particularly studied for applications because they have low noise and a high repetition frequency of GHz–THz. We applied this stable pulse light source to time division multiplexing (TDM) communications and achieved 2-channel multiplexing. We also clarified that it is possible to select any channel from the multiplexing pulse train and to receive it.

Key words: Microresonator; Microcomb; Dissipative Kerr soliton; Time division multiplexing

1. Introduction

Microresonators can confine and store light by using resonance. A whispering gallery mode (WGM) resonator is one of the microresonators and the light in the resonator stays when its circumference is equal to an integer multiple of the wavelength.

An optical frequency comb can be generated by a microresonator. It has equally spaced spectrum like a comb, and it is an optical pulse train which has a high repetition frequency in the time domain. A microresonator-based comb, which is called a microcomb, was first reported in 2007 [1]. It is necessary to mode lock for oscillating microcomb as a pulse, and the mode-locked microcomb is called a dissipative Kerr soliton (DKS) or soliton comb. DKS is generated by sweeping the laser wavelength from the short wavelength side of the resonance wavelength to the long wavelength side. DKS is applied to various field such as distance measurement [2], spectroscopy [3], and optical synthesizer [4].

Especially in the application to optical communications, the DKS is promising to be used for wavelength division multiplexing (WDM) communications [5] because it has low noise and a precisely defined comb spacing. It can be also applied to time division multiplexing (TDM) communications because it has a high repetition frequency of GHz–THz. In this study, we generated a DKS with an MgF₂ microresonator, and multiplexed the 2 channels.

2. Generation of dissipative Kerr solitons

To generate the DKS continuously, it is necessary to sweep the laser wavelength and to lock it in the region where the soliton step can be observed. Therefore, we used a method called the Pound-Drever-Hall technique, in which a sideband is generated at the laser wavelength using a phase modulator and the laser wavelength is stabilized

in the soliton region by locking the sideband to the resonance wavelength. Figure 1 shows the optical spectrum of the soliton comb's sech^2 envelope generated by the MgF₂ microresonator. The inset shows the repetition frequency of 9.6 GHz. The pump wavelength contained in the soliton comb was removed by the fiber Bragg grating and the comb excluding the pump was used for transmission.

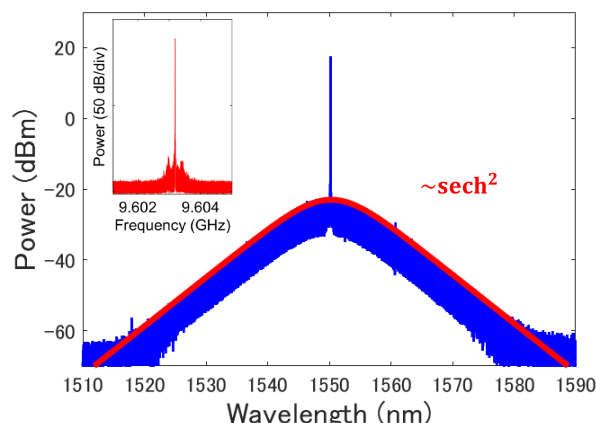


Fig. 1 Optical spectrum of the soliton comb. The red line is sech^2 envelope of the spectrum. The inset shows RF spectrum at 9.6 GHz.

3. Synchronization of clock frequency by external input

To demonstrate TDM communications, it is necessary to perform modulation/demodulation and signal extraction with a frequency equal to the repetition frequency of the soliton comb. Therefore, we configured the experimental setup shown in Fig. 2(a) and verified whether a clock frequency and the repetition frequency could be synchronized. The comb was separated for trigger and measurement, and the signal for trigger was received and input to the pulse pattern generator

(PPG). The signal output from PPG was input to the trigger of the sampling oscilloscope via the error detector. The signal for measurement was received by a wideband photodetector (PD) and the pulse waveform was observed. The observed pulse waveform is shown in Fig. 2(b). The pulse interval is 103.7 ps, which corresponds to the repetition frequency of 9.6 GHz. From this result, it was confirmed that it is possible to synchronize the repetition frequency of the soliton comb on the receiving side.

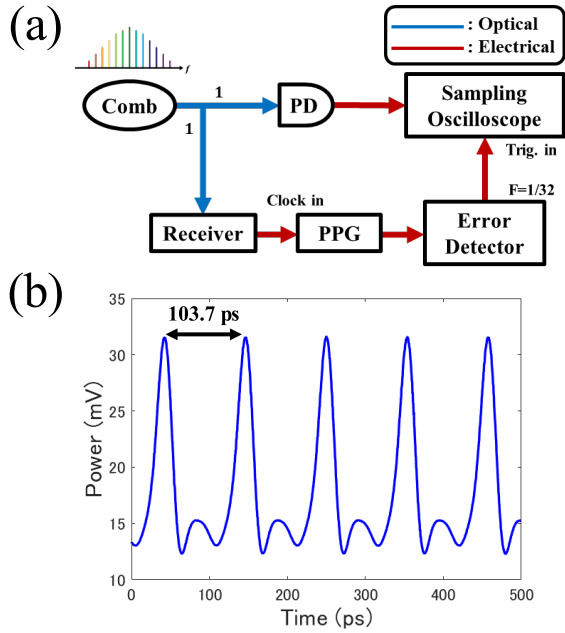


Fig. 2(a) Experimental setup for synchronizing the clock frequency on the receiving side. PD: Photodetector. PPG: Pulse Pattern Generator. (b) Soliton comb pulse waveform observed with the sampling oscilloscope. The repetition time is 103.7 ps, which corresponds to the repetition frequency of 9.6 GHz.

4. Results of non-multiplexing transmission

As a preliminary step to multiplexing 2 channels, we conducted an experiment to modulate and transmit a soliton comb without multiplexing. Figure 3(a) shows the experimental setup. As in the previous experiment, the comb is separated for trigger and transmission, the signal for transmission is amplified by an erbium-doped fiber amplifier (EDFA), and the delay is adjusted by an optical delay line. After adjustment, it was modulated with an intensity modulator. The signal output from PPG was used for intensity modulation. At this time, the modulation frequency was synchronized by inputting the repetition frequency of the comb to PPG. The modulated signal passed through a 40 km dispersive-shifted fiber (DSF) and was received, and then the bit error rate (BER) was measured by an error detector. Figure 3(b) shows the measurement results of BER. The blue plot shows

the BER of back-to-back (B2B), and the green plot shows the one of 40 km transmission. Error-free (BER < 10^{-9}) was observed in both B2B and 40 km. In addition, almost no power penalty was observed in the transmission of 40 km. Thus, it was confirmed that the pulse transmission of the soliton comb is possible by using the dispersion-shifted fiber.

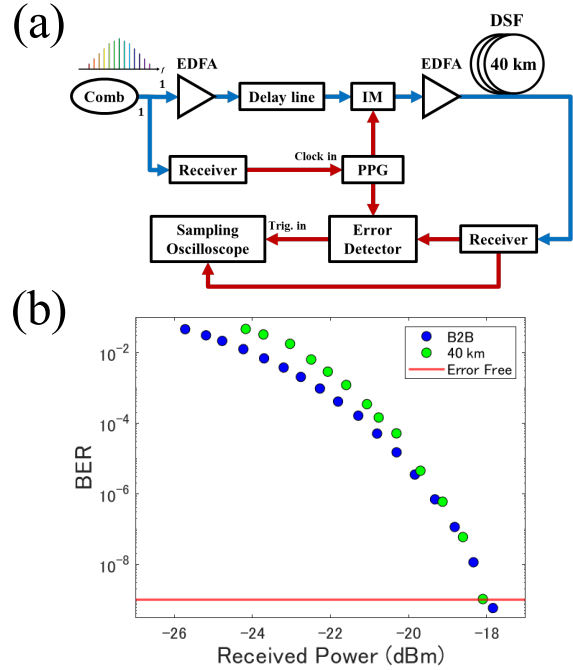


Fig. 3(a) Experimental setup for non-multiplexed transmission of soliton pulse signal. EDFA: Erbium-doped Fiber Amplifier. IM: Intensity Modulator. PPG: Pulse Pattern Generator. DSF: Dispersion-shifted Fiber. (b) BER measurement results by error detector. The blue plot shows the result of back-to-back, and the green plot shows the one of 40 km transmission.

5. 2-channel multiplexing

Figure 4(a) shows an experimental setup for multiplexing 2 channels. The soliton comb separated for transmission was amplified by EDFA and demultiplexed into two channels by a 3 dB coupler. One channel was not modulated, and only the other channel was intensity modulated, and then the two channels were multiplexed again by the coupler. Figure 4(b) shows the measurement results of the multiplexed waveforms. Waveforms with a large amplitude are non-modulation components, and waveforms with a small amplitude are modulation components. The unmodulated components and the modulated components are arranged alternately. The multiplexed pulse train was incident on the intensity modulator, and the modulated channel was selected and transmitted by adjusting the optical delay line. After receiving the selected signal with PD, the eye pattern was measured.

The results are shown in Fig. 4 (c). A slightly open eye could be observed, but the eye pattern was not sufficient to measure BER. The waveform below the eye is considered to be ASE noise due to EDFA.

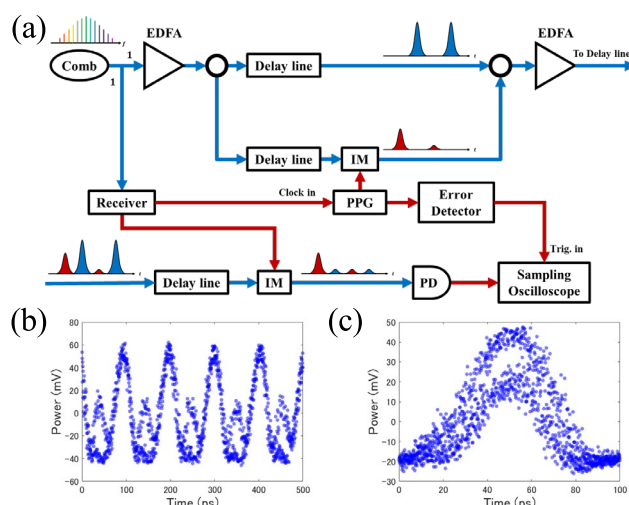


Fig. 4(a) Experimental setup for 2-channel multiplexing. EDFA: Erbium-doped Fiber Amplifier. IM: Intensity Modulator. PPG: Pulse Pattern Generator. PD: Photodetector. (b) Multiplexing results of unmodulated pulse train and modulated pulse train observed with the sampling oscilloscope. (c) Eye pattern of the modulated signal selected by the intensity modulator.

6. Summary

We generated the soliton comb which has a repetition frequency of 9.6 GHz by using the MgF₂ microresonator and achieved the synchronization of the clock frequency and error-free non-multiplexed transmission. We also clarified that it is possible to select and receive any channel from the 2-channel multiplexed optical signal. However, since it was not possible to observe an eye pattern worthy of measuring BER in 2-channel multiplex transmission, it is necessary to perform verification to eliminate noise, such as by introducing a band-pass filter.

References

- [1] P. Del’Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth and T. J. Kippenberg, *Nature* **450** 1214–1217 (2007).
- [2] P. Trocha, M. Karpov, D. Ganin, M. H. P. Pfeiffer, A. Kordts, S. Wolf, J. Krockenberger, P. Marin-Palomo, C. Weimann, S. Randel, W. Freude, T. J. Kippenberg, and C. Koos, *Science* **359**, 887–891 (2018).
- [3] Q. Yang, M. Suh, K. Y. Yang, X. Yi, and K. J. Vahala, *Science* **354**, 600–603 (2016).
- [4] D. T. Spencer, T. Drake, T. C. Briles, J. Stone, L. C. Sinclair, C. Fredrick, Q. Li, D. Westly, B. R. Ilic, A. Bluestone, N. Volet, T. Komljenovic, L. Chang, S. H. Lee, D. Y. Oh, M. Suh, K. Y. Yang,

M. H. P. Pfeiffer, T. J. Kippenberg, E. Norberg, L. Theogarajan, K. Vahala, N. R. Newbury, K. Srinivasan, J. E. Bowers, S. A. Diddams and S. B. Papp, *Nature* **557** 81–85 (2018).

- [5] P. Marin-Palomo, J. N. Kemal, M. Karpov, A. Kordts, J. Pfeifle, M. H. P. Pfeiffer, P. Trocha, S. Wolf, V. Brasch, M. H. Anderson, R. Rosenberger, K. Vijayan, W. Freude, T. J. Kippenberg and C. Koos, *Nature* **546** 274–279 (2017).

Detuning and noise measurement in a microcomb

Soma Kogure (M1)

Optical frequency combs generated in optical microresonators, or microcombs have revolutionized photonics. Microcombs have a few states depending on the detuning, or the frequency difference between pump light and resonance. In this work, the noise characteristics of a microcomb was investigated.

Key words: Microresonator, Microcomb, Kerr comb, Soliton comb

1. Introduction of microcomb

Optical frequency combs are light with equidistance frequency modes, and they are called so because the spectra are identical to hair combs. There are some conventional frequency combs namely Titanium Sapphire mode-lock laser, fiber comb, electro-optic comb. Some alternatives with smaller footprint were desired and in 2007, the microcomb was demonstrated using microresonator reducing overall size drastically [1]. Since the microresonators have smaller cavity length, the free spectral range (FSR) is much higher compared to the existing frequency combs spanning from a few GHz to 1 THz.

There are a few states which microcombs have namely a Turing pattern combs, a modulation instability (MI) comb, and a soliton comb [2]. The noise characteristics of microcomb is largely determined by the state of microcomb. Soliton combs can achieve mode-locked state and have excellent coherence. Therefore, many applications have been realized using soliton combs including optical communications, mm-wave generation, and dual-comb spectroscopy. One notable drawback of a soliton comb is low conversion efficiency. The average output power of a soliton comb is determined regardless of the input power. On the other hand, a MI comb can be generated more efficiently in spite of the high noise. Our laboratory has reported on the results of the comparison between a soliton comb and MI combs [3]. Optical data transmission experiment was demonstrated using one of the comb lines from each microcomb. In the experiment, we used two distinctive MI combs phases 1 and 2. It turned out that although the MI comb phase 1 exhibited bit error rates of 10^{-9} comparably to soliton comb, the MI comb phase 2 performed poorly with bit error rates of 10^{-2} and it is unsuitable for a light source.

The main distinction between the two MI combs is the detuning. Detuning is the parameter of frequency difference between pump light and resonance on which the state of microcomb depends. Generally, in microresonator optics, pump light is injected from the shorter wavelength and swept toward the longer wavelength due to the thermal shift of the resonance. In that case, the pump light is in blue-detuned range where Turing pattern combs and MI combs exist. Further sweep leads to a state called red detuning, in which the pump light surpasses the resonance, and a soliton comb is generated (Fig. 1).

The difference between MI comb phases 1 and 2 is

detuning. The latter one has smaller detuning with higher intracavity power, which results in much noisier comb lines. However, few studies have addressed the relationship between the detuning and noise characteristics.

In this work, I report on the result of an experiment for detuning and noise characteristics measurement to give some insight into the microresonator physics.

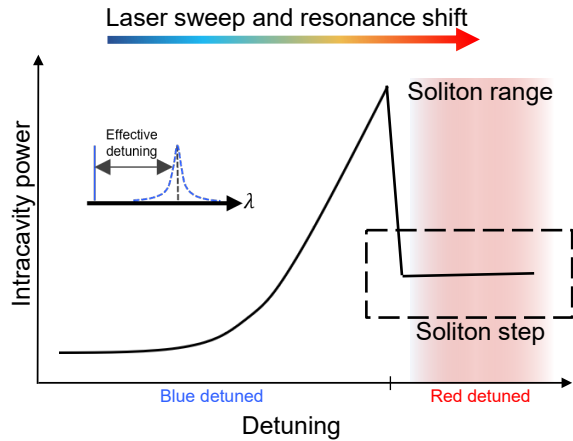


Fig. 1: As the pump laser is swept towards longer wavelength, the intracavity power increases. In blue-detuned range, Turing pattern combs and MI combs exist, whereas in red-detuned regime, soliton combs appear.

2. Detuning measurement method

First, I would like to explain the method of detuning measurement. The term “detuning” refers to the frequency difference between thermally shifted resonance wavelength and pump light wavelength, or effective detuning.

There are several methods to measure detuning, but I used a network analyzer (NA) here [4]. It was originally developed to confirm the generation of soliton comb and its detuning, but it also can be applied to MI comb.

Simplified experimental setup is shown in Fig. 1. The pump light is phase modulated by the electrical signal from NA, amplified by an EDFA (Erbium doped fiber amplifier), and then injected into the resonator. The transmitted light is received with a photodetector (PD). The generated photocurrent is monitored by the NA. to see the frequency components.

When the pump light $A \exp i\omega t$ is phase modulated by the NA output signal $B \sin \Omega t$, the phase modulated pump light is expressed as follows: $A \exp(i\omega t + B \sin \Omega t)$. In frequency domain, two sidebands are

produced on both side of the pump light with the spacing of Ω . If this light is received by a PD, only a DC component with a magnitude of A^2 would be generated. However, when the output frequency of the NA matches the detuning, one of the sidebands is trapped inside the resonator, and the beating signal between the pump and the other sideband is observed on the NA. Therefore, one distinctive peak appears whose frequency correspond to the detuning. When a soliton comb is present, two peaks called *C*- and *S*-resonance are observed.

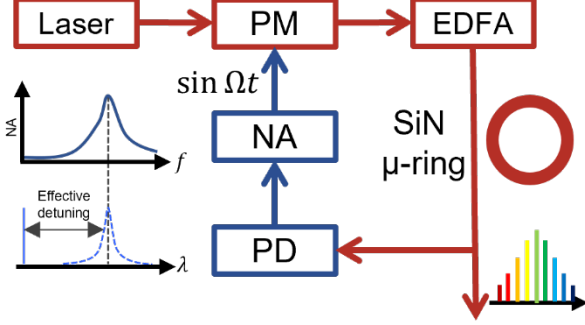


Fig. 2: Experimental setup for detuning measurement with a network analyzer. The frequency of the peak on the network analyzer corresponds to the detuning. PM; Phase modulator, EDFA; Erbium doped fiber amplifier, NA; Network analyzer, PD; Photo detector.

3. Generation of microcombs and detuning measurement

In this study, a silicon nitride resonator was used for microcomb generation. It has a microring with a diameter of 182 μm or FSR 400 GHz. The waveguide dimension is $1.6 \times 0.8 \mu\text{m}^2$. Q factor is 1.5×10^6 as shown in Fig. 3.

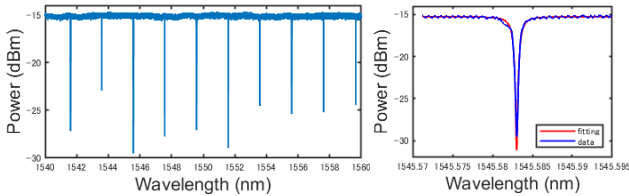


Fig. 3: Measured spectrum of the resonator. Q factor is 1.5×10^6 or 125 MHz in linewidth.

The results of the detuning measurement and the spectrum of the generated microcombs are shown in Fig. 4. As the detuning becomes smaller, the MI combs grow.

In addition, to examine the characteristics of the comb line, the comb component around 1525 nm was filtered out from the microcombs using a bandpass filter, and the beat noise and line width were measured. Beat noise here refers to fluctuations in the intensity of the comb line. It is caused by the presence of light within the same longitudinal mode, which originated from the different primary comb lines. For linewidth measurement, a delayed self-heterodyne method was used with the delay of a 2-km single mode fiber. The results are shown in Fig. 5

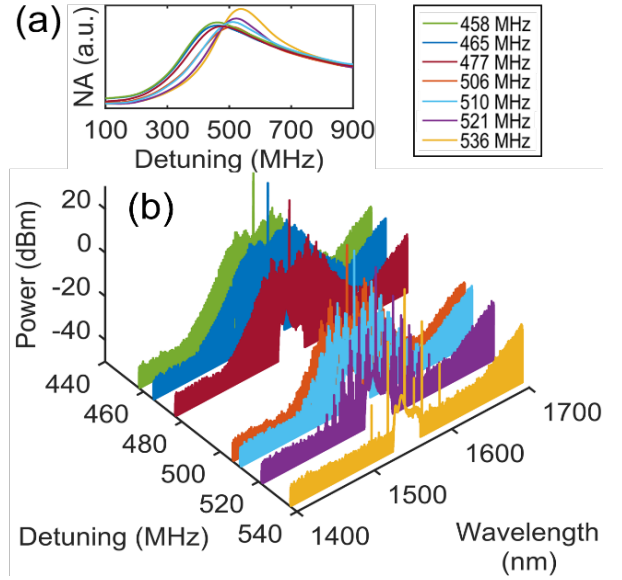


Fig. 4: (a) Detuning measurement results. (b) The spectra of generated microcombs. They are offset according to the detuning.

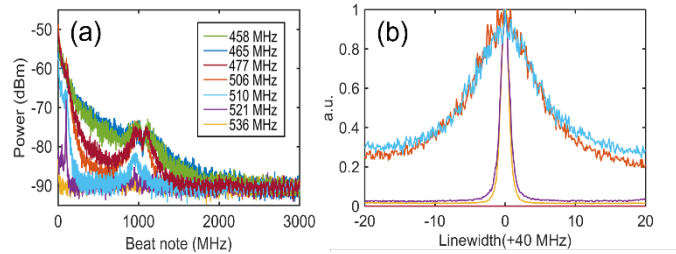


Fig. 5: (a) Beat noise measurement results. (b) Linewidth measurement results by a delayed self-heterodyne method (RBW: 1 MHz).

Fig. 5(a) shows that the floor of beat noise begins to rise when the detuning is 477 MHz and 506 MHz. The linewidth measurement results (Fig. 5(b)) show that the linewidth is about 5 MHz when the detuning is 506 MHz, while the linewidth widens so dramatically at 477 MHz that the . From these results, it is suggested that the noise of the MI comb deteriorates significantly when the detuning becomes smaller than around 500 MHz for this resonator.

4. Conclusion

The noise characteristics of MI combs largely depend on the detuning. In this work, detuning and noise characteristics measurement was combined to see the relationship between the two. In this case, the noise deteriorates substantially when the detuning is smaller than around 500 MHz.

References

- [1] P. Del'Haye, *et al.* Nature **450**, 1214-1217 (2007).
- [2] T. Herr, *et al.* Nat. Phot. **8**, 145-152 (2014).
- [3] S. Fujii, *et al.* Opt. Express **30**, 1351-1364 (2022).
- [4] H. Guo, *et al.* Nat. phys. **13**, 94-103, (2017).

WDM transmission with a microcomb in an MgF_2 microresonator

Shun Tasaka (M2) Koya Tanikawa(B4)

Microcombs, which are optical frequency combs using microresonators, are smaller, more energy-efficient, and have higher repetition rates than conventional optical frequency combs. Various application studies utilizing these features have been reported. In this study, WDM transmission experiments using the IM-DD method were conducted for microcombs generated from a microresonator made of MgF_2 , and transmission characteristics were measured.

Key words : microresonator, MgF_2 , microcomb, WDM

1. Background

An optical frequency comb is an optical pulse train on the time axis with components that are strictly equally spaced on the frequency axis, and there are several ways to generate it. An optical frequency comb obtained based on the principle of nonlinear optical effects caused by the strong confinement of light inside a microresonator is called a microcomb. Compared with conventional optical frequency comb using mode-locked lasers, microcombs based on micro optical resonators are compact, energy-saving, and highly repetitive, and since the mode-locking of microcombs[1] was demonstrated, they have been used in spectroscopy[2], LiDAR[3], and planetary exploration[4] and various other application studies have been reported.

Because the frequency characteristics of microcomputers can be multiplexed, research has also been conducted on applications in WDM transmission. Conventional WDM transmission requires as many light sources as the number of multiplexes, but by replacing them with microcomputers, power consumption can be reduced. Most of the previous studies on optical communication applications using microcomputers have targeted high-capacity, long-distance transmission using digital coherent communication [5], while low latency, reliability, and cost performance are required for medium-distance transmission in data centers. In this research, MgF_2 was selected as the resonator material because the dense comb line spacing of microcombs using MgF_2 crystal resonators has the potential to be a light source for high-density WDM transmission, and the IM-DD WDM communication using microcombs with MgF_2 microresonators was demonstrated for practical application in medium-distance transmission. Experiments were conducted and transmission characteristics were measured.

2. Method

A schematic of the experiment is shown below. Originally, the generated microcomb must be

stabilized by feedback control, but that system is omitted here.

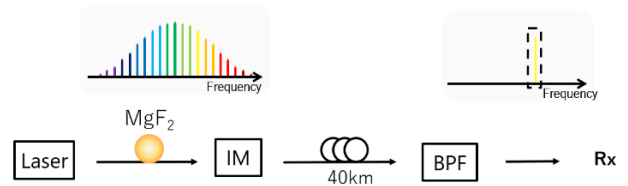


Fig. 1. Experimental schematic. BPF: band pass filter; IM: intensity modulator; Rx: photodetector, including transceiver and error detector.

Microcombs generated by an MgF_2 microresonator were used as carriers for WDM transmission, amplified by an EDFA (omitted in the figure), intensity modulated, amplified again by an EDFA, and transmitted 40 km over a fiber. The bit error rate (BER) was measured with an error detector, and the eye pattern was measured with a sampling oscilloscope. In the measurement, a variable attenuator was installed just before the transceiver to gradually lower the light-receiving power, and the relationship between the light-receiving power and BER was monitored each time. Error-free transmission (excellent transmission characteristics) was defined as a BER value of 10^{-9} or less.

3. Result

Experiments were first conducted using an MgF_2 microresonator with FSR of 9.6 GHz. The spectrum of the microcomputer used in the experiment is shown below.

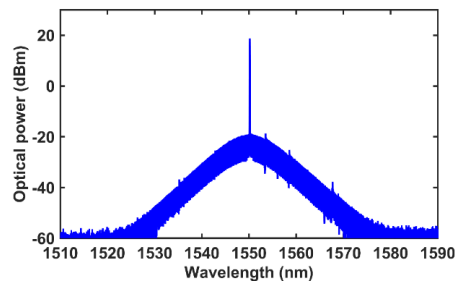


Fig. 2. Microcomb generated by microresonator with

FSR of 9.6 GHz.

A microcomb covering the entire C-band was obtained using a light with a wavelength of 1,550 nm as a pump. Before modulating the intensity of the microcomb, only the pump light is removed using a fiber Bragg grating (FBG).

The following table shows the BER measured back-to-back (modulated light is input directly to the receiver without interrupting the 40 km transmission line) when the comb component with a wavelength of 1550.330 nm is extracted and the modulation rate (bit rate) is varied between 7 and 10 Gbps.

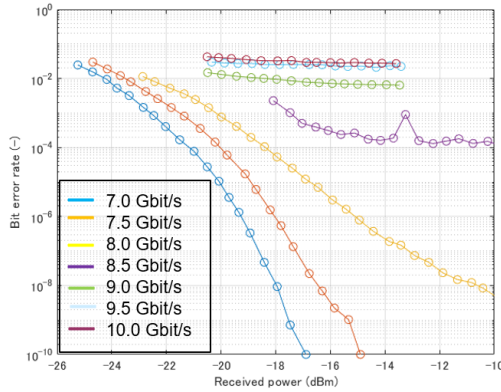


Fig. 3. Back-to-back BER obtained by modulating a microcomb with a microresonator with FSR of 9.6 GHz to different modulation rates.

Error-free transmission was achieved at modulation speeds of 7.0 Gbps and 7.5 Gbps. When the modulation rate was increased, the transmission characteristics were likely to have deteriorated due to crosstalk from adjacent comb lines.

Next, experiments were conducted using an MgF₂ microresonator with an FSR of 20.1 GHz. The spectrum of the microcomputer used in the experiment is shown below.

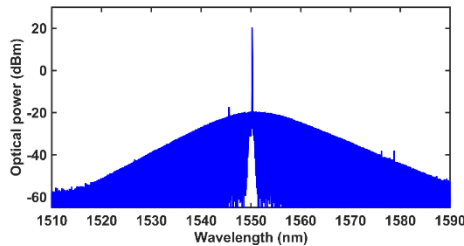


Fig. 4. Microcomb generated by FSR at 20.1 GHz with a microresonator.

The BER and eye pattern measured at a wavelength of 1548.020 nm for the comb component are shown below when the modulation rate is 10 Gbps and the comb component is varied by moving the center wavelength of the variable bandpass filter.

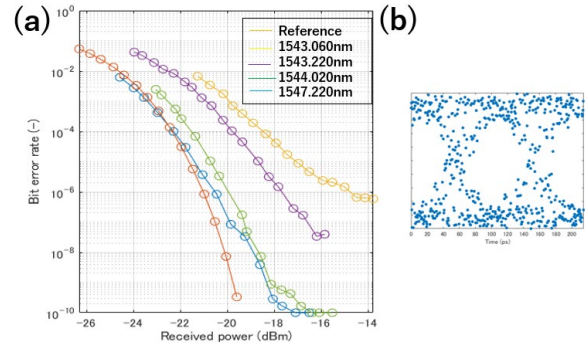


Fig. 5. (a) BER obtained by isolating the comb components at different wavelengths from a microcomb with an FSR of 20.1 GHz. the orange line is the BER measured back-to-back with the pump light for reference. (b) Eye pattern measured at 1548.020 nm wavelength for the comb component.

As shown in the transmission results for the 1547.220 nm wavelength comb component in blue in the figure, error-free transmission was achieved for several wavelength components. Conversely, the comb component with a wavelength of 1,543.060 nm, shown in yellow, has a BER stuck at around 10^{-6} , indicating poor transmission characteristics. The comb components that could not achieve error-free operation due to deteriorated transmission characteristics were identified in the wavelength range away from the pump wavelength, where the power of the comb component becomes small, and in the range close to the pump wavelength, where it is strongly affected by the pump light cutout and ASE noise.

4. Conclusion

Error-free transmission was achieved in WDM transmission with a modulation rate of 7 Gbps per comb line for the FSR 9.6 GHz microcomb and 10 Gbps per comb line for the FSR 20.1 GHz microcomb. The spacing of the comb lines is 0.08 nm and 0.16 nm, respectively, indicating the potential of MgF₂ microresonators for high-density and spectrally efficient WDM transmission for communication applications.

Reference

- [1] T. Herr et al., Nat. Photon. 8, 145-152 (2014).
- [2] M.-G. Suh et al., Science 354, 600-603 (2016).
- [3] P. Trocha et al., Science 359, 887-891 (2018).
- [4] M.-G. Suh *et al.*, Nat. Photon. **13**, 25-30 (2019).
- [5] P. Marin-Palomo *et al.*, Nature **546**, 274-279 (2017).

Soliton comb generation in a crystalline resonator integrated with a piezoelectric actuator

Koshiro Wada (M2)

A micro-comb is an optical frequency comb light source generated with an optical micro-resonator which is composed of precisely equally spaced frequencies. In particular, each of its frequencies is phase-locked, which is called a soliton comb. It is necessary to sweep a laser frequency to specific region which exists on the lower side of a resonant mode. In this study, the soliton comb generation is realized by sweeping the resonant mode to soliton regime with a method called as a mechanical frequency tuning.

Key words: optical micro-resonator; micro-comb; soliton comb; frequency tuning

1. Abstract

Optical microresonators are optical devices with ultra-high Q values and small mode volumes that can efficiently generate nonlinear optical effects. In particular, the generation of micro-combs, which are optical frequency comb sources generated by four-wave mixing when a single frequency light is injected into the resonator (Fig.1(a)), has attracted much attention. Above all, the state in which each of comb lines is phase-locked is called a soliton comb, and is expected to be applied as an ultra-short pulsed laser with high repetition rates in the GHz to THz band [1].

There are various platforms for generating soliton comb, I used a crystalline resonator which has a higher Q value theoretically. It can generate soliton comb with less power consumption because the threshold intensity for generating soliton comb is inversely proportional to the square of Q value, and it is known that soliton comb generated in it has very low phase noise.

For generating soliton comb, it is necessary to sweep a laser frequency to specific region called “soliton regime” which exists on the lower side of a resonant mode. When considering modularization, it is desirable to use a fixed frequency laser that has a smaller footprint than a tunable frequency laser, but it seems impossible in principle. However, a method called frequency tuning, which sweeps a resonant mode against a fixed frequency laser, can be used to make this possible.

The resonant frequency depends on refractive index and structure of the resonator, and it can be swept by continuously changing them. The method can be divided

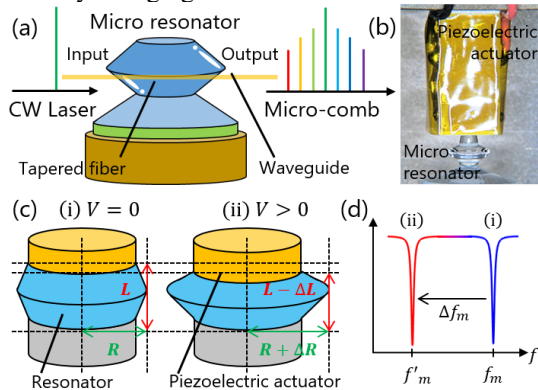


Fig.1: (a) Conceptual figure of micro-comb generation. (b) Picture of a crystalline resonator coupled with a piezoelectric actuator. (c) Conceptual figure of mechanical frequency tuning. (d) Conceptual diagram of resonance frequency tuning.

into temperature controlled and mechanical controlled methods, the former being called thermal frequency tuning and the latter mechanical frequency tuning [2]. In crystalline resonator, the delay due to thermal propagation is too large to achieve a sufficient sweep speed of resonant mode for generating soliton comb, and the power consumption is large because the entire system is bulky. On the other hand, if the resonator is structurally controlled by applying an external force with a piezoelectric actuator (Fig. 1(c), (d)), fast and low power tuning of the resonant frequency can be expected.

In this study, I used mechanical frequency tuning to generate a soliton comb by sweeping the resonant mode at high speed against highly stable fixed frequency laser.

2. Mechanical frequency tuning

First, a demonstration experiment of mechanical frequency tuning was conducted. The setup is shown in Fig. 2(a), where light is coupled through a tapered fiber to crystalline resonator coupled with piezoelectric actuator. A sinusoidal voltage was applied to piezoelectric actuator, resulting in the transmission waveform of the resonant mode shown in Fig. 2(b). Since the interference waveform by MZI for laser frequency reference is not observed, it is clear that the transmission waveform is due to the resonant mode sweep for the fixed frequency laser.

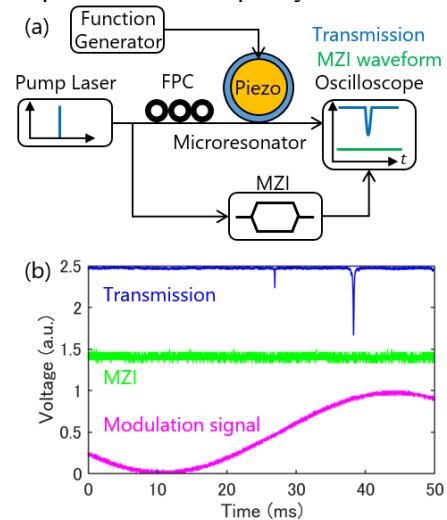


Fig.2: (a) Mechanical frequency tuning setup; FPC: Fiber Polarization Controller; MZI: Mach-Zehnder Interferometer. (b) Transmission waveform of the resonant mode obtained by tuning the resonant frequency.

3. Soliton comb generation

Next, soliton comb was generated by mechanical frequency tuning. The setup is shown in Fig. 3(a), where a fixed-frequency laser amplified to sufficient intensity by EDFA is injected into the resonator and a triangular voltage is applied to piezoelectric actuator. This is called a soliton step, and soliton comb can be obtained by stopping the sweep of the resonant mode in the red-colored range (soliton regime). The tuning efficiency of the resonant frequency in this case was about 20 MHz/V, as shown in Fig. 3(c), so soliton comb can be generated by applying a voltage of a few volts at most.

The soliton comb was obtained by stopping the frequency sweep of the resonant mode in the soliton regime during the soliton step. The frequency spectrum is shown in Fig. 3(d) and the RF spectrum in Fig. 3(e). The soliton comb was feedback-free and lasted for several minutes, with a repetition rate of 15.55 GHz.

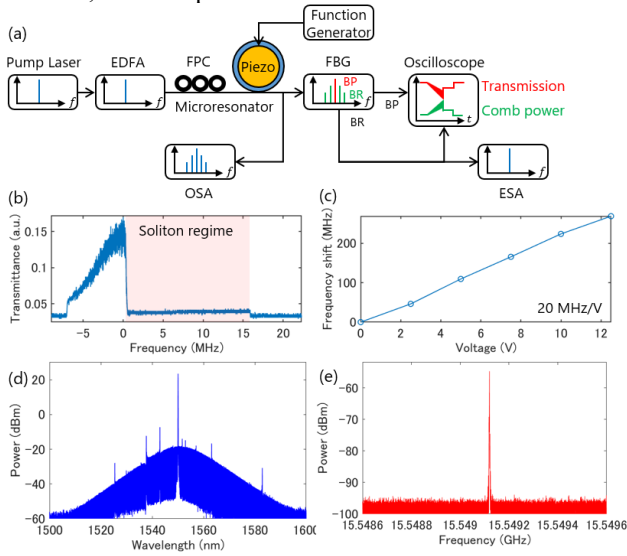


Fig.3: (a) Setup for soliton comb generation by mechanical frequency tuning; EDFA: erbium-doped fiber amplifier; FPC: fiber polarization controller; FBG: fiber Bragg grating. (b) Soliton step generated by mechanical frequency tuning. (c) Tuning efficiency of resonant modes. (d) Frequency spectrum of the generated soliton comb and (e) RF spectrum.

4. Conclusion

In this study, the generation of soliton comb by mechanical frequency tuning was achieved using a crystalline resonator coupled with a piezoelectric actuator with no feedback system.

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References

- [1] T. Herr, et al, Nat. Phot. 8, 145-152 (2014)
- [2] J. Liu, et al, Nature 583, 385-390 (2020)
- [3] S. B. Papp, et al, Phys. Rev. X 3, 031003 (2013)

Study of the Er-doped microresonator and saturable absorber for mode-locked laser

Keigo Nagashima (M2)

In this study, we aim to develop a mode-locked laser by doping a microresonator with erbium to enable self oscillation and using the saturable absorption characteristics of CNT. Therefore, we clarified the fabrication method of Er-doped resonators and investigated the measurement method of saturable absorption properties of CNT-coated resonators.

Key words: Microresonator; Mode-locked laser; Saturable absorber; Erbium doped device

1. Background

Mode-locked lasers have many possible applications, including optical communications, spectroscopy, and LiDAR. There are several methods to realize mode-locking, including the use of a solid-state Ti-sapphire laser [1] and a fiber laser [2]. One drawback of these mode-locked lasers, however, is their low repetition rate of several hundred MHz. Since the repetition rate is inversely proportional to the resonator size, we thought that the development of a passive mode-locked laser using a microresonator, which can confine light to a small area, would enable us to obtain a very high repetition rate of over 100 GHz.

The goal of this study is to achieve passive mode-locked by adding Er to the gain medium, enabling self-excited oscillation at 1550 nm using a pump light at 1480 nm, and achieving passive mode-locked oscillation by the saturable absorption property of carbon nanotubes (CNTs), which are characterized by their ability to transmit intense light and absorb low-intensity light. (Fig. 1). The laboratory has previously fabricated a resonator using an Er-doped silica film and observed oscillation at around 1550 nm. Here, we describe a new method of adding Er to the resonator using a sol-gel method. In saturable absorption, CNTs are mixed with PDMS and coated on the toroid resonator, and the saturable absorption property of CNTs is also observed. However, the currently observed modulation depth is not optimized for mode-locking, and smaller modulation depths need to be measured. Here, we describe the results of our investigation of a measurement method for this purpose.

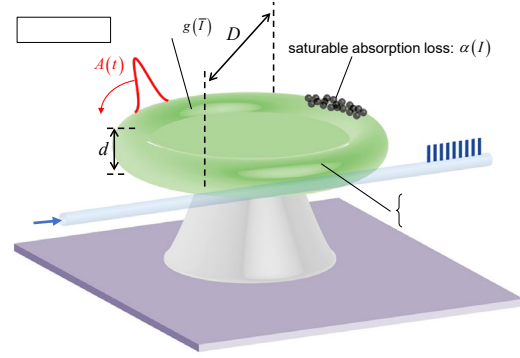


Fig. 1 Schematic illustration of on-chip mode-locked laser with CNT and Er-doped microtoroid.

2. Er-doped microresonator

In our laboratory, Er-doped silica films were prepared by a sol-gel method, and the silica films were subjected to photolithography, BHF etching, XeF2 etching, laser reflow

The toroid resonator was fabricated by By inserting a 1480 nm pump light into the fabricated Er-doped toroid resonator, oscillation was observed around 1550 nm. The results are shown in Fig. 2. The red color shows the Er concentration of $1.7 \times 10^{18} \text{ cm}^{-3}$ in the starting solution, and the blue color shows the Er concentration of $0.85 \times 10^{18} \text{ cm}^{-3}$. Both resonator diameters are about 70 μm , and the oscillation efficiencies are 1% and 0.6%, respectively. The oscillation threshold is about 5 μW in both cases.

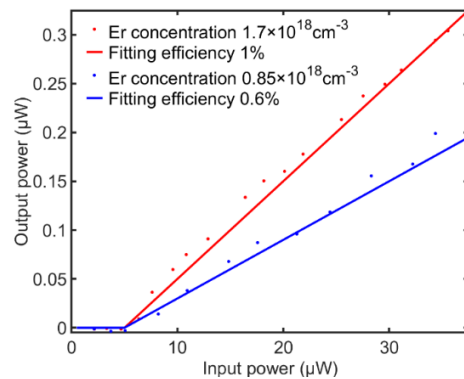


Fig. 2 Oscillation efficiency of Er-doped microresonator.

However, changes in the experimental environment during film fabrication caused a problem that prevented the fabrication of a uniform film as shown in Fig. 3(a). As a countermeasure, the atmosphere during spin-coating was adjusted by vaporizing ethanol, the solvent of the starting solution, and a uniform film was successfully fabricated as shown in Fig. 3(b).

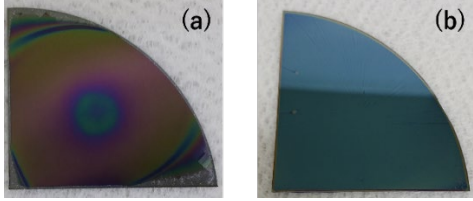


Fig. 3 Differences in the surface of Er-doped silica films due to different atmospheres during spin-coating.

By adjusting the atmosphere, a uniform film was successfully deposited, but it was not thick enough to fabricate a resonator. Therefore, Er-doped resonators were fabricated by fabricating disk resonators using conventional thermally oxidized silica films and coating their surfaces with a uniform film. In this method, the concentration of Er cannot be estimated from the starting solution, but it is possible to estimate the effective concentration of added Er from the oscillation efficiency using a model from a previous study [3]. The relationship between the oscillation efficiency and Er concentration is shown in Fig. 4.

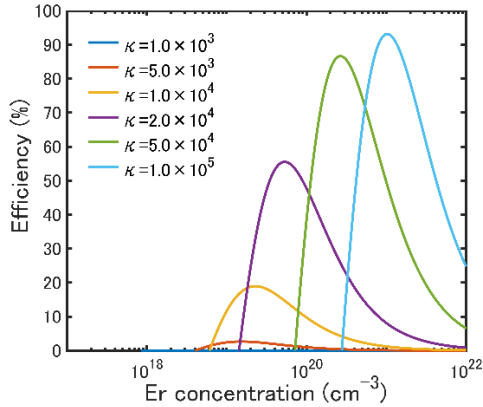


Fig. 4 Relationship between Er concentration per unit volume and oscillation efficiency.

3. Saturable absorption properties of CNTs

In the past, we have observed saturable absorption properties of CNTs mixed with PDMS and coated on toroidal resonators. The modulation depth per resonator roundtrip was 3.2×10^{-3} . These results and the simulation results considering the gain per roundtrip of the Er-doped resonator are shown in Fig. 5.

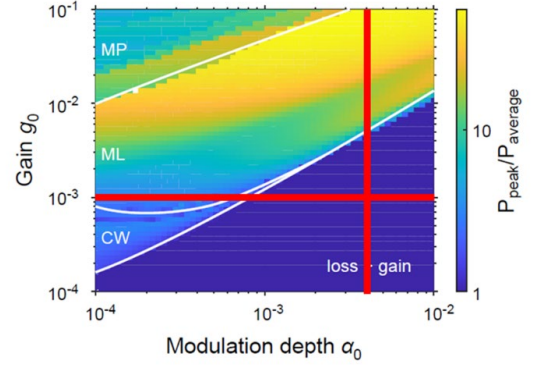


Fig. 5 Analysis results for mode-locked condition.

In this map, the horizontal axis represents the modulation depth per resonator roundtrip, and the vertical axis represents the gain per resonator roundtrip. The lines in red are the experimental gain and modulation depth, respectively. The results show that the modulation depth should be reduced by about one order of magnitude as a parameter to reach the target mode locking area (ML). Therefore, it is necessary to experimentally measure smaller modulation depths. Currently, the modulation depth per roundtrip is converted with the change in Q -factor of the resonator, and it was found necessary to measure a smaller change in Q -factor. Therefore, to measure the Q -factor more accurately, I tackled each problem with two goals : to suppress the oscillation of the tapered fiber for coupling with the resonator, and to stabilize the pump intensity input to the resonator.

For the oscillation of the tapered fiber, I changed the jig used to hold the tapered fiber in place. The distance between the fixation points of the tapered fiber was 115 mm in the previously used fixture, but a new fixture was fabricated to reduce the distance to 45 mm. To quantitatively evaluate the stability of the coupling, the toroid resonator without saturable absorber coating were placed close to the tapered fiber, scanned multiple times at different wavelengths for the same resonance mode, and the variation was measured. The results are shown in Fig. 6 (c), which shows the variation measured multiple times, and although there is one outlier for every 10 scans, the Q factor is suppressed to within 0.06×10^6 from 1.54×10^6 to 1.60×10^6 , approximately. This result translates into a modulation depth per roundtrip It can be said that the measurement is possible if the modulation depth is 2.1×10^{-5} or higher.

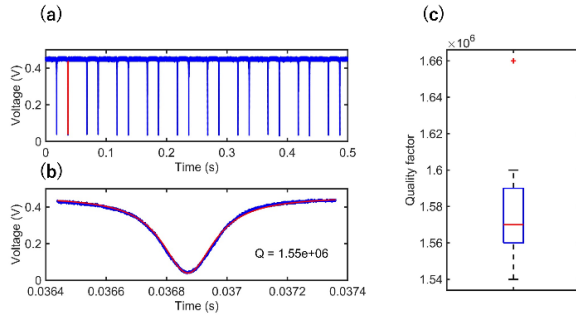


Fig. 6 After changing the fixture for tapered fibers variation in Q -factor.

The pump intensity input to the resonator was stabilized by matching the wavelength of the pump light to the resonance wavelength using the PDH locking method, which is more stable than the conventional measurement method. After stabilizing the pump light intensity, the toroid resonator was coated with CNTs at a concentration of 0.03 mg/ml, and the results of measuring the change in Q factor are shown in Fig. 7. mode while gradually decreasing the input power.

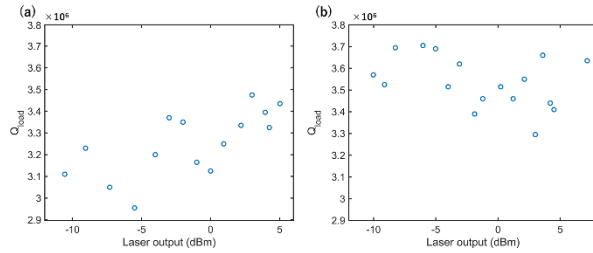


Fig.7 Variation of Q -factor of CNT coated resonator with input power.

The results show that although the Q factor varies with input power, the Q factor is not the same at the same input power. This suggests that the change in Q factor is due to factors other than saturable absorption, and I conclude that a CNT concentration of 0.03 mg/ml is difficult to achieve saturable absorption characteristics, and that a more concentrated CNT is necessary to achieve saturable absorption characteristics.

References

- [1] U. Keller, G. W. 'tHooft, W. H. Knox, and J. E. Cunningham, Opt. Lett. **16**, 1022–1024 (1991).
- [2] F. Wang, A. G. Rozhin, V. Scardaci, Z. Sun, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, Nature Nanotechnology **3**, 738–742 (2008).
- [3] B. Min, T. J. Kippenberg, L. Yang, K. J. Vahala, J. Kalkman, and A. Polman, Phys. Rev. A **70**, 033803 (2004).

Perfect soliton crystal induced by saturable absorption effect

Ayata Nakashima (M1)

By confining light in a microresonator, mode-locked pulses called dissipative Kerr solitons can be generated from a continuous-wave. However, due to a chaotic process, their number and intervals are usually random, which reduces a power and an efficiency. This study revealed that by adding a saturable absorption effect, dissipative Kerr solitons can be equally spaced, which is suitable for applications.

Key words: Dissipative Kerr soliton; Saturable absorption; Soliton crystal

1. Introduction

A microresonator can confine light in a tiny area. With this device, stable mode-locked pulses called dissipative Kerr solitons (DKSs) can be generated from a continuous-wave (CW) [1]. Therefore, they are expected to be applied in various fields such as spectroscopy, optical communications, and distance measurements. However, the conversion from CW to DKS usually results in a multi-soliton, where multiple DKSs exist at various intervals. This state is undesirable for applications because of the spectral interferences. For this reason, much research has focused on the generation of regularly spaced DKSs, called a perfect soliton crystal (PSC) [2].

In this study, we proposed a new approach to generate a PSC. As shown in Fig. 1, we aimed to realize a PSC without a complicated experimental setup by using a microresonator with a saturable absorber. By conducting a numerical analysis, we found that saturable absorbers made it possible to generate PSC. Furthermore, we revealed that the number of DKSs that constitute the PSC could be switched by adjusting the input power.

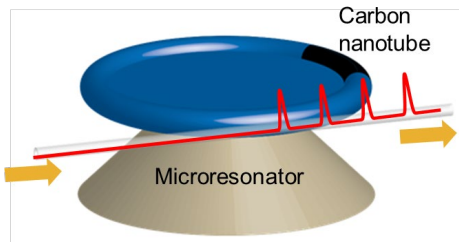


Fig. 1: Schematic illustration of a microresonator doped with a saturable absorber.

2. Simulation model

Light propagating in a cavity with a saturable absorber is modeled as

$$T_r \frac{\partial E}{\partial t} = \left(-\frac{\alpha_{\text{tot}}}{2} - \frac{\alpha_{\text{SA}}}{1 + |E|^2/P_{\text{sat}}} - i\delta_0 - \frac{iL\beta_2}{2} \frac{\partial^2}{\partial \tau^2} + iL\gamma|E|^2 \right) E + \sqrt{\theta} E_{\text{in}}. \quad (1)$$

Since we assumed an SiO₂ toroidal cavity with

carbon nanotubes (CNTs), we set roundtrip time T_r to 9.05 ps, the loss α_{tot} to 2.2×10^{-4} , the modulation depth of CNTs q_0 to 4.0×10^{-3} , the saturation power of CNT P_{sat} to 4.46 W, the resonator length L to $600\pi \mu\text{m}$, the dispersion β_2 to $-17.7 \text{ ps}^2/\text{km}$, the nonlinear coefficient γ to $0.003 \text{ W}^{-1}\text{m}^{-1}$, the coupling coefficient θ to 5.5×10^{-5} , and the input power $|E_{\text{in}}|^2$ to 70 mW. Equation 1 was calculated using a split-step Fourier method, and we simulated a DKS generation.

3. Results

First, we investigated a DKS generation in a resonator without a saturable absorber by ignoring the second term on the right-hand side of Eq. 1. The result is shown in Fig. 2. First, a periodic waveform called Turing rolls was generated from a CW input. However, when the normalized detuning $\delta (=2\delta_0/\alpha_{\text{tot}})$ increased, the waveform was disturbed. When the pump wavelength exceeded the resonance wavelength of the resonator, stable DKSs were generated.

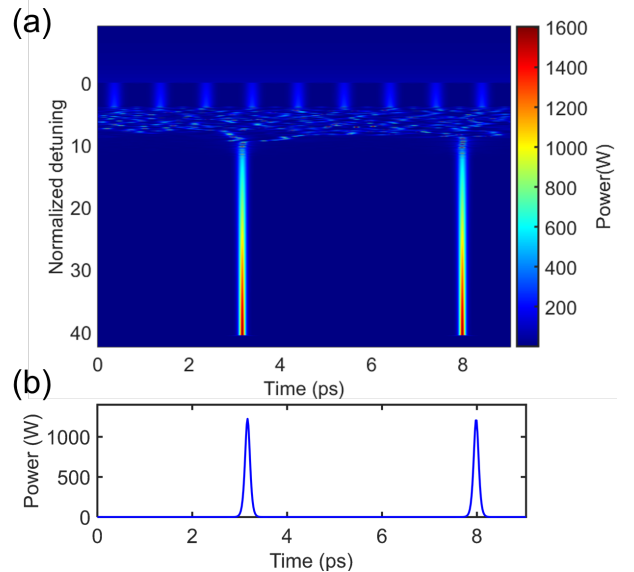


Fig. 2: (a) DKS generation in a microresonator without a saturable absorber. (b) 2-DKSs formed in the resonator.

On the other hand, the behavior of a light in a resonator with a saturable absorber was

significantly different as shown in Fig. 3. After Turing rolls appear, DKSs were directly generated. Since Turing rolls have a periodic waveform with eight peaks, the final number of DKSs was also eight. In other words, when a saturable absorber is added, the final number of DKSs is related to the period of Turing rolls. This implies that the final number of DKSs can be controlled by changing the parameter such as an input power or a cavity dispersion.

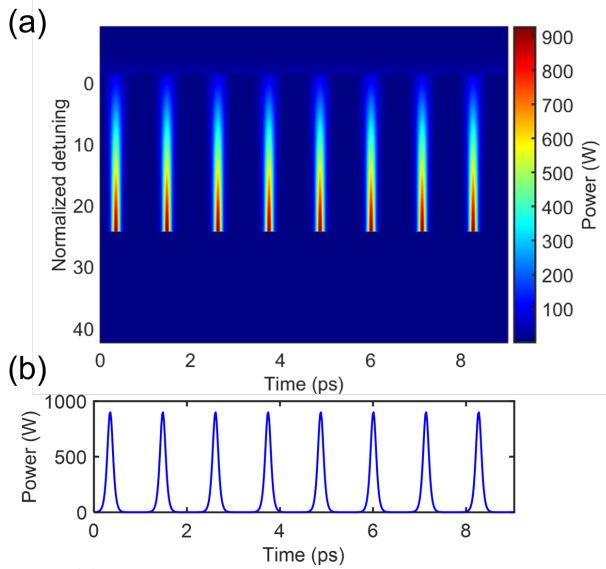


Fig. 3: (a) DKS generation in a microresonator with a saturable absorber. (b) PSC formed in the resonator.

To investigate the effect of a saturable absorber, we repeated the wavelength sweep at a constant pump power P_{in} until the normalized detuning reached δ . Each point (δ, P_{in}) in Fig. 4 indicates the number of peaks of the generated waveform. In the DKS state, the number of peaks is equal to the number of DKSs. However, in the chaotic region, the number is relatively large because it corresponds to the number of peaks of random waveforms. When the system passes through the chaotic region, the number of peaks changed from calculation to calculation, resulting in a mosaic pattern. On the other hand, without passing through a chaotic region, the number of peaks is deterministic, and the area is represented by a single color. Thus, based on the information on the number of peaks, we classified the regions into several state.

In the case of no saturable absorber, multiple DKSs were randomly generated after exceeding a red line where the effective detuning was zero. On the other hand, when a saturable absorber was present, the input power required for DKS formation increased due to the additional loss of the saturable absorber. However, there was a new region where the same number of DKSs as the peak number of Turing rolls was maintained. In this region, the number of Turing rolls varied with

the pump power. However, when the input power was too high, the saturable absorption effect was not sufficient to support the PSC formation, and a random number of DKSs were generated as in the case of DKS generation in a resonator without a saturable absorber.

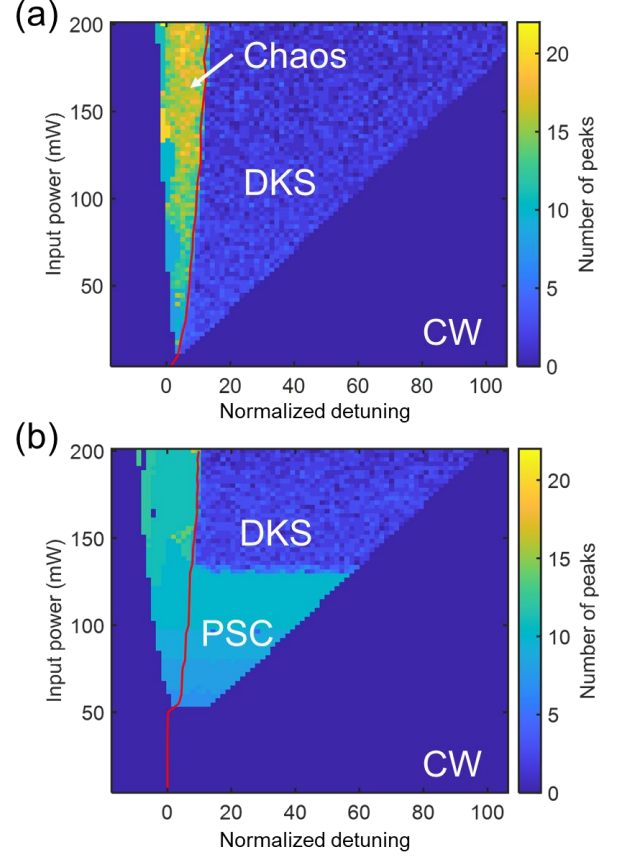


Fig. 4: Number of peaks of the waveform in the resonator. (a) Without a saturable absorber. (b) With a saturable absorber.

4. Summary

This study investigated a DKS generation in a microresonator with a saturable absorber. We found that a saturable absorption effect made it possible to directly generate PSCs without passing through a chaotic region. And since the number of DKSs constituting PSC is related to the initial Turing rolls, the number of DKSs can be controlled by changing the pump intensity or the cavity dispersion. This is useful for realize a laser with the characteristics of high efficiency, high power, and high repetition rate.

References

- [1] T. Herr, V. Brasch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, *Nat. Photonics* **8** 145 (2014).
- [2] D. C. Cole, E. S. Lamb, P. Del'Haye, S. A. Diddams, and S. B. Papp, *Nat. Photonics* **11** 671 (2017).

Statistical Data

Publications (Apr. 2021 – Mar. 2022)

Journal papers

- [1] Y. Hayama, S. Fujii, T. Tanabe, and Y. Kakinuma, "Theoretical approach on the critical depth of cut of single crystal MgF_2 and application to a microcavity," *Precision Engineering*, Vol. 73, pp. 234-243 (2022).
- [2] T. S. L. P. Suzuki, A. Nakashima, K. Nagashima, R. Ishida, R. Imamura, S. Fujii, S. Y. Set, S. Yamashita, and T. Tanabe, "Design of a passively mode-locking whispering-gallery-mode microlaser," *J. Opt. Soc. Amer. B*, Vol. 38, No. 10, pp. 3172-3178 (2021). [arXiv:2106.06943 (2020)].

International conferences

- [1] T. Tanabe, "Ultrahigh-Q crystalline whispering gallery mode microcavity fabricated with mechanical machining," 6th International Workshop on Microcavities and Their Applications (WOMA 2022), Hong Kong (hybrid), Feb. 7-9 (2022). (invited)
- [2] S. Sugawara, S. Tanaka, S. Fujii, H. Kumazaki, S. Tasaka, S. Kawanishi, and T. Tanabe, "Optical transmission using Stokes light," International Symposium on Novel maTerials and quantum Technologies (ISNTT2021), S08-4, online, Dec. 14-17 (2021).
- [3] S. Kogure; T. Ohtsuka; S. Fujii; H. Kumazaki, K. Wada, Y. Hashimoto, Y. Kobayashi, T. Araki, K. Furusawa, N. Sekine, and T. Tanabe, "Comparison of microcomb-based light sources for optical data transmission," *Frontiers in Optics + Laser Science (FiO/FS 2021)*, FM1B.1, online, Oct. 31-Nov. 4 (2021).
- [4] R. Imamura, K. Nagashima, and T. Tanabe, "Measurement of saturable absorption behavior of CNT/PDMS coated high-Q microcavity towards mode-locking of Er-doped laser," 11th International Conference on Metamaterials, Photonic Crystals and Plasmonics (META2021), Warsaw, Jul. 20-23 (2021). (invited)
- [5] R. Imamura, A. Nakashima, K. Nagashima, T. S. L. P. Suzuki, R. Ishida, S. Fujii, and T. Tanabe, "Design of a Passively Mode-locked Microlaser with an Er-doped Microcavity and Carbon Nanotubes," *Conference on Lasers and Electro-Optics - European Quantum Electronics Conference (CLEO/Europe - EQEC 2021)*, CF-4.6, online, Jun. 21-25 (2021).
- [6] S. Tanaka, S. Fujii, K. Wada, H. Kumazaki, S. Kogure, S. Tasaka, T. Ohtsuka, S. Kawanishi, and T. Tanabe, "Optical Data Transmission with a Dissipative Kerr Soliton in an Ultrahigh Q MgF_2 Microresonator," *Conference on Lasers and Electro-Optics - European Quantum Electronics Conference (CLEO/Europe - EQEC 2021)*, CI-1.4, online, Jun. 21-25 (2021).
- [7] A. Nakashima, S. Fujii, R. Imamura, K. Nagashima, and T. Tanabe, "Stable formation of multiple solitons in an optical microresonator assisted by saturable absorption," *CLEO:2021*, SW4A.3, online, May 9-14 (2021).
- [8] S. Kogure, T. Ohtsuka, S. Fujii, H. Kumazaki, K. Wada, Y. Hashimoto, Y. Kobayashi, T. Araki, K. Furusawa, N. Sekine, and T. Tanabe, "Optical data transmission with a microresonator-based comb source," *International Conference on Nano-photonics and Nano-optoelectronics (ICNN2021)*, ICNN-6-02, online, Apr. 19-21 (2021).
- [9] S. Tanaka, S. Fujii, K. Wada, H. Kumazaki, S. Kogure, S. Tasaka, T. Ohtsuka, S. Kawanishi, and T. Tanabe, "Optical data transmission with a dissipative Kerr soliton in an ultrahigh-Q MgF_2 microresonator," *The 10th*

Advanced Lasers and Photon Sources (ALPS2021), ALPS-P-19, online, Apr. 19-21 (2021).

- [10] S. Sugawara, S. Tanaka, K. Wada, S. Fujii, H. Kumazaki, S. Tasaka, S. Sota, T. Ohtsuka, S. Kawanishi, and T. Tanabe, "Raman-comb-based wavelength source for optical communication," The 10th Advanced Lasers and Photon Sources (ALPS2021), ALPS-12-05, online, Apr. 19-21 (2021).
- A. Nakashima, S. Fujii, R. Imamura, K. Nagashima, and T. Tanabe, "Generation of multiple solitons with help from a saturable absorber," The 10th Advanced Lasers and Photon Sources (ALPS2021), ALPS-9-02, online, Apr. 19-21 (2021).

Awards

- [1] May 2021 The 10th Advanced Lasers and Photon Sources, Best Student Award, Shuya Tanaka

Dissertations

Master thesis:

Koki Yube, “Quantum Memory Using Coupled Resonators for the Integration of Time-Multiplexed Heralded Single-Photon Sources”

Takumasa Kodama, “Multiwavelength Analysis Using Disordered Photonic Crystal Waveguides”

Shota Sota, “Fabrication of SiN Ring Resonators for Two-Tone Signal Generation in Frequency-Tunable THz Sources”

Koichiro Wada, “Frequency Tuning and Soliton Comb Generation Using Crystalline Resonators Coupled to Piezoelectric Actuators”

Shun Tasaka, “Application of Magnesium Fluoride Crystalline Resonators to Wavelength-Division Multiplexed Optical Communications”

Keigo Nagashima, “Gain and Saturable Absorption for the Development of Mode-Locked Lasers Based on Optical Microresonators”

Shuya Tanaka, “High-Efficiency Wavelength-Division Multiplexed Optical Communications Using Optical Frequency Combs from Magnesium Fluoride Microresonators”

Bachelor thesis:

Nao Okuya, “Performance of Hydrogen Gas Sensors Based on Optical Microresonators at Low Hydrogen Concentrations”

Atsushi Takano, “Design and Optical Characterization of SiN Ring Resonators for Soliton Comb Generation”

Yuki Tate, “Mode-Locking in Coupled Optical Microresonators with Gain and Saturable Absorption”

Koya Tanikawa, “Optical Frequency Combs Generated in Magnesium Fluoride Microresonators and Their Application to High-Capacity Optical Communications”

Ryo Nishihata, “Coupling of Si and SiN Waveguides Using Inverse Tapers”