



Annual Report on Research Activities 2020 (Volume 10)



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Foreword

I would like to express our sincere gratitude for the generous support and interest you have shown in the research activities of the Tanabe Photonic Structures Laboratory in the Department of Electronics and Electrical Engineering at Keio University's Faculty of Science and Technology.



The year 2020 was significantly impacted by the global spread of COVID-19. In our lab, we took on new challenges, including moving meetings online. If we view this as an opportunity to combine online platforms with science and technology, we may discover new possibilities. In fact, international conferences are now attracting participants from around the world, enabling us to share our research findings with audiences previously beyond our reach. In the 2020 academic year, I served as the Program Chair for the CLEO conference held in May. Since my student days, I have regarded CLEO as one of the most important conferences in our field, so it was a great honor to take on this role. By hosting the conference online and waiving attendance fees, we welcomed participants from all over the world and enjoyed a successful event—an example, I believe, of the new opportunities these circumstances can bring.

In this report, we present the specific research findings from the 2020 academic year. The report was primarily prepared by our students, and we have endeavored to preserve their original text as much as possible. Although it may be considered somewhat “handmade,” I hope you will find it enlightening. If you are interested in our activities, please feel free to contact us.

September 2021
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Research Activities

Ultra-precision machining fabrication of ultrahigh-Q crystalline microresonators

Shun Fujii (D3)

Ultra-precision machining technology opens the possibility of attaining a dispersion-engineered ultra-high-quality factor optical microresonator. Here, we report on the recent progress regarding the all-precision-machining fabrication of crystalline microresonators. The observed Q exceeds 100 million for both magnesium fluoride and calcium fluoride materials, which is the highest Q -value fabricated solely by machining process. This method promises advanced dispersion engineering for microcavity nonlinear optics and paves the way for realizing microresonator-based comb applications.

Key word: Microresonator, Four-wave mixing, Dispersion engineering

1. Introduction

Ultrahigh- Q optical microresonators have been an attractive platform for studying linear and nonlinear and quantum optics in the past few decades. While microresonator fabrication techniques have evolved with various materials in the recent years, the crystalline microresonators, particularly crystalline whispering gallery mode resonators, are generally fabricated by manual polishing method yet. Such a conventional fabrication process inhibits precise control of the resonator structure, and thereby complicating advanced dispersion engineering for nonlinear applications including Kerr frequency comb generation.

One promising solution of this limitation is to employ ultra-precision machining for microresonator fabrication. In the case of conventional fabrication method, namely cut-and-polish method, a diamond tool enables us to form whispering gallery structures, whereas we need to employ subsequent manual polishing with diamond slurry to improve the Q factor. Meanwhile, precision machining readily overcomes the limitation of a manual process since the entire process is undertaken with a computer-controlled system. Thus, precision machining has readily achieved the predesigned resonator structures needed for fabricating single-mode and dispersion-engineered resonators.

Here, we report on ultrahigh- Q microresonator fabrication by all-precision machining [1]. We obtain smooth resonator surface with a few nanometer scales by pursuing the ideal cutting condition and undertaking both an orthogonal cutting experiment and a precise cylindrical turning experiment. The results offer cutting parameters optimized for fluoride crystal-based microresonator fabrication.

2. Investigation of ideal cutting condition and resonator fabrication

A particularly essential parameter for fabricating a single-crystal resonator is the critical depth of cut (DOC). The cutting mode can be classified into two classes by the DOC at which the transition from ductile-mode to brittle-mode cutting emerges during the cutting process. A smooth crack-free surface can be obtained only in the ductile regime, whereas the surface quality becomes worse, namely rough and cracked, in the brittle regime. Since the fluoride crystals used as a resonator material are hard and brittle, they are challenging as regards obtaining

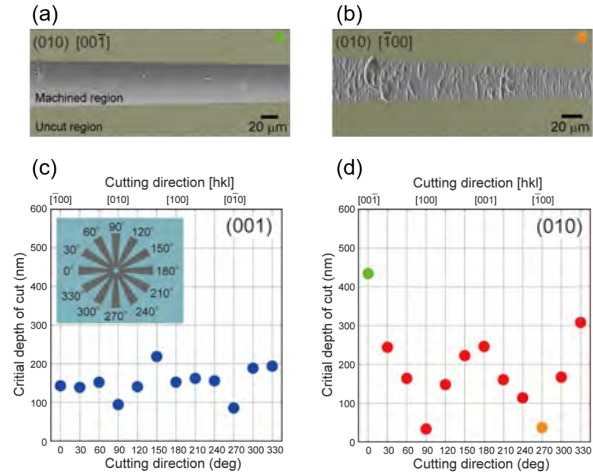


Fig. 1: (a-b) Scanning electron micrographs showing machined surfaces of a (010) plane in the [001] direction and [1⁰⁰] direction. (c-d) The measured critical depth of cut versus cutting direction on a (001) and (010) plane, respectively. The inset shows schematics of the cutting direction.

a smooth surface that promises ultrahigh Q values.

First, we investigate the critical DOC on different crystal planes to determine the minimum cutting depth, which is required for maintaining the ductile mode cutting for an MgF_2 workpiece. The crystal planes are (001) and (010), and the 0-degree directions are set at [1⁰⁰] and [001[^]], respectively. Although the only difference is the cutting direction, we can see a significant impact on the surface quality of machined region as shown in Figs. 1(a) and 1(b). Figures 1(c) and 1(d) show the critical DOC variation as a function of cutting direction on each plane. The variation in critical DOC originates from the crystal anisotropy that determines the slip system and cleavage plane of single crystal. Based on the results, we conclude that the cutting depth must be kept at less than approximately 50 nm to maintain ductile mode cutting in single-crystal MgF_2 for every cutting directions and planes.

Second, we performed cylindrical turning experiment to investigate the optimum turning condition with which to achieve a completely smooth cylindrical surface. An MgF_2 workpiece with an end-face orientation of (001) was mounted to an ultraprecision aspheric surface machine (ULG-100 E, TOSHIBA MACHINE) [Figs. 2(a) and 2(b)]. Our ultraprecision machining consists of a three-part turning process. After rough turning process, finish turning is performed in the ductile mode to complete the ultraprecise turning under a 50 nm

DOC. It should be noted that various settings such as the rotation speed, feed rate, and diamond tool condition are considered as well as the DOC. Then, the surface roughness was measured at 15-degree intervals from orientation flat [100] defined as 0 degrees [Fig. 2(c)]. As shown by the red dots in Fig. 2(d), large roughness exceeding 200 nm appears after rough turning. On the other hand, finish turning performed with ductile cutting greatly reduces the surface roughness, and the obtained RMS roughness is less than 2 nm at 18 observation points (blue dots in Figs. 2(d)). An observed periodicity of 90 degrees is due to the crystal anisotropy of an MgF_2 crystal, and the further optimization of cutting parameters circumvent the emergence of such anisotropy. Based on the cylindrical turning experiment, we fabricate crystalline microresonators using the same ultraprecision machine. Although asymmetric surface quality may lead to degradation of the Q factor, we finally achieved a 100 million Q with the present cutting parameters.

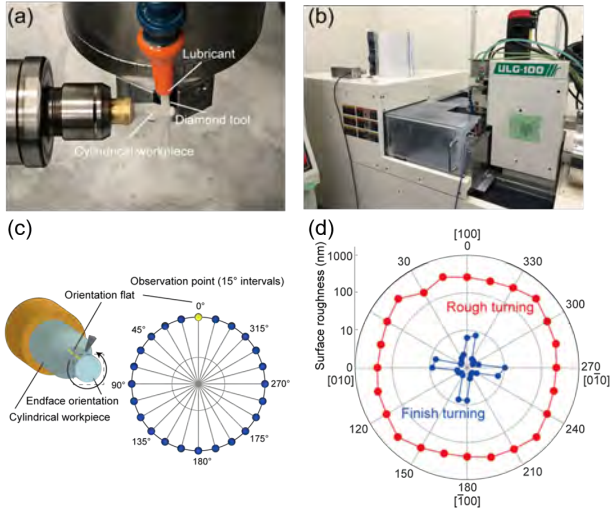


Fig. 2: (a-b) Ultra-precision aspheric surface machine for cylindrical turning. (c) Schematic of surface roughness measurement. (d) Measured surface roughness (RMS) of the finish turning (blue dots) and rough turning (red dots) regions.

3. Q-factor and dispersion measurement of fabricated resonators

Then, the fabricated resonators undergo Q-factor and dispersion measurement. The Q-factor and dispersion are obtained from a resonator transmission spectrum as a resonance linewidth and relative resonance frequencies, respectively. We observe transmission light through a tapered optical fiber waveguide, and the frequency axis is calibrated with a wavelength-meter and a fiber-based Mach-Zehnder interferometer. The frequency calibration is essential technique to measure the linewidth and dispersion precisely.

Figures 3(a)-3(c) represent scanning electron microscope (SEM) images of the fabricated crystalline microresonators by precision machining. The lorentzian fitting yield loaded quality factors corresponding to 1.39×10^8 and 1.09×10^8 for MgF_2 and CaF_2 , respectively, as indicated in Figs. 3(d) and 3(e). We want to emphasize that the obtained Q is the highest value recorded in a crystalline WGM microresonator fabricated solely by

ultraprecision machining. The measured dispersion can be expressed as the integrated dispersion D_{int} , which is usually used to represent the dispersion as a function of the relative mode number μ , as $D_{\text{int}} = (1/2)D_2\mu^2 + (1/6)D_3\mu^3 + (1/24)D_4\mu^4 + \dots$. Here, D_1 is the resonator FSR, D_2 is the second-order dispersion, D_3 and higher-order terms correspond to higher-order dispersion [2]. As shown in Fig 3(f), the experimental result agrees well with the simulation values, and such a feature is one of the predominant advantages of computer-controlled machining. Moreover, we can exploit the fabrication technique for more advanced dispersion engineering. To this end, we fabricated triangular CaF_2 resonator with an apex of 120 degrees (Figs. 3(b) and 3(c)). The dispersion also agrees with the designed value. However, the obtained Q value is unfortunately limited to 10 million, indicating that the cutting parameter should be further optimized for such advanced structures. As a future challenge of this study, a sophisticated geometry design benefits us to realize anomalous dispersion in a shorter wavelength regime or a smaller size resonator, enabling the bandwidth expansion of a microresonator frequency comb.

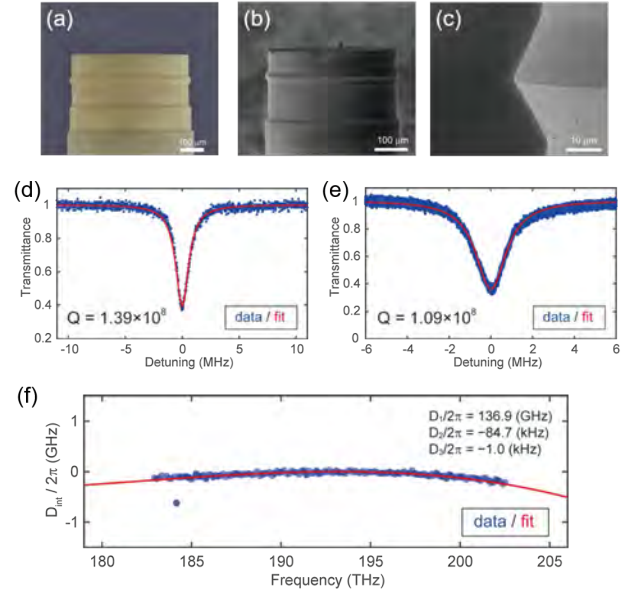


Fig. 3: (a) False-color SEM image of a fabricated MgF_2 microresonator. (b-c) SEM images of a fabricated triangular CaF_2 resonator with an apex of 120 degrees. (d-e) Normalized spectra of the fabricated MgF_2 (d) and CaF_2 (e) resonator, respectively. (f) Measured dispersion D_{int} versus frequency of the fabricated MgF_2 resonator.

4. Conclusion

In conclusion, we reported on ultrahigh-Q crystalline microresonator fabrication realized by all-precision machining. The observed Q reaches 100 million, which is in principle sufficient value to obtain a microresonator frequency comb. We believe that our fabrication technique paves the way to attaining compact, broadband, and efficient microcomb generators.

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WDM transmission with a soliton comb in an MgF_2 microresonator

Shuya Tanaka (M2), Shun Tasaka (M1)

After the demonstration of soliton mode-locking (soliton comb), various applications of optical frequency comb based on optical microresonators have been studied. Telecommunication applications are still of great interest because of the advantages of soliton combs. In this study, we performed IM-DD, WDM transmission with a soliton comb generated from an optical microresonator made of MgF_2 and measured its transmission characteristics.

Key word: microresonator, MgF_2 , soliton comb, WDM, IM-DD

1. Introduction

Optical resonators are mechanism that confine light of specific wavelengths inside via resonance phenomena. Among these, "microresonators" fabricated in the size range of mm to nm can easily generate nonlinear optical effects due to the strong light confinement. The main materials are magnesium fluoride (MgF_2), silica (SiO_2), and silicon nitride (SiN). On the other hand, "optical frequency combs" are light that have precisely equidistant components on the frequency axis (and optical pulse trains on the time axis due to the Fourier transform). In particular, the optical frequency combs obtained from the cascaded Kerr effect, a kind of nonlinear optical effects, in a microresonator are called "microcombs". The pulse repetition rate matches the resonant mode spacing of the resonator and can reach from GHz to THz. Optical frequency combs obtained from existing light sources, such as Ti:sapphire lasers, typically have a repetition rate of several hundred MHz, so the difference is obvious. In 2014, T. Herr et al. demonstrated soliton mode-locking of microcombs for the first time, which paved the way for a wide range of applications [1], including spectroscopy [2,3], optical frequency counting [4], low-noise RF oscillation [5], ranging (e.g., LIDAR) [6], optical synthesizers [7], planetary exploration [8], and even quantum applications [9]. Microcombs with soliton mode-locking (henceforth called "soliton combs") are attracting attention as ultrafast pulsed light sources with great potential [10].

Among the various applications of soliton combs, communication applications have been the mainstream for a long time. In other words, each frequency (wavelength) component (comb line) of a microcomb is regarded as an optical carrier for wavelength division multiplexing (WDM) communications. In conventional WDM communications, it is necessary to prepare many lasers (and their controllers) for each wavelength to be multiplexed, but the microcomb-light source replaces these with a single input laser and a microresonator, thus significantly reducing power consumption. Light transmission methods can be broadly classified into the intensity modulation-direct detection (IM-DD) method and the digital coherent method. Before the demonstration of the soliton mode-locking, microcomb communication has already been attempted, and there are previous studies on both methods [11,12]. Soliton combs have the advantage that the phase of each component is aligned and the line width of each component is narrow, so it is mainly used for high-capacity digital coherent communication [13]. Researches on the transmission with different forms of

soliton combs such as dark pulses [14] and soliton crystals [15], as well as researches on the combination of soliton combs with the latest optical communication technologies [16] have been reported.

Most of the previous studies have been conducted on digital coherent communications using soliton combs with microresonators made of SiO_2 or SiN , and there are only a few examples using MgF_2 [17]. However, in an MgF_2 microresonator, the wavelength spacing of the comb component can be made as close as around 10 GHz, which is an advantage in securing more carriers in a limited bandwidth and achieving higher bandwidth utilization (spectral efficiency). To demonstrate this advantage, in this study, we performed WDM communication using a soliton comb in an MgF_2 microresonator and evaluated the transmission characteristics. The transmission method is the IM-DD method, aiming at future medium-distance transmission applications in, such as, data centers.

2. Method

A schematic diagram of the experiment is shown below. Originally, the generated soliton comb must be stabilized by feedback control, but that system is omitted here.

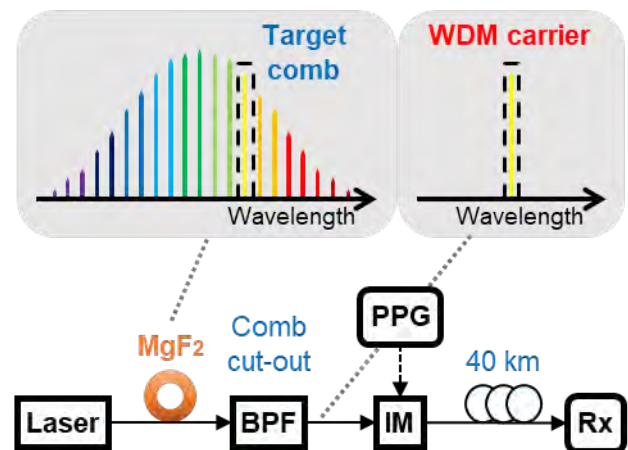


Fig. 1: Schematic of the experiment. One of the lines of a soliton comb is cut out, intensity-modulated and transmitted 40 km, and the BER and eye diagrams are obtained at the receiver. BPF: band-pass filter, PPG: pulse pattern generator, IM: intensity modulator, Rx: receiver (transceiver and error detector).

By adjusting the center wavelength and bandwidth of the variable bandpass filter, a single wavelength light was

obtained by cutting out one of the lines of the soliton comb. This was used as a WDM carrier, amplified by an EDFA (omitted in the figure), intensity modulated, amplified again by an EDFA, and then transmitted 40 km through the fiber. The modulation speed (bit rate) was set to 10 Gbps. Eye diagrams were measured with a sampling oscilloscope. For the BER measurement, a variable attenuator was installed just before the transceiver to gradually lower the received power, and each time the received power was lowered, the relationship between the received power and the BER was monitored. When the BER value became less than 10^{-9} , it was considered as error-free transmission (excellent transmission characteristics).

For wavelength multiplexing, the center wavelength of the bandpass filter was moved one after another to shift the comb line to the next, and the transmission was performed with a time difference. The variable wavelength range was set to C-band (1,530-1,565 nm).

3. Result

The actual soliton comb spectrum and RF spectrum generated from the MgF_2 microresonator are shown below.

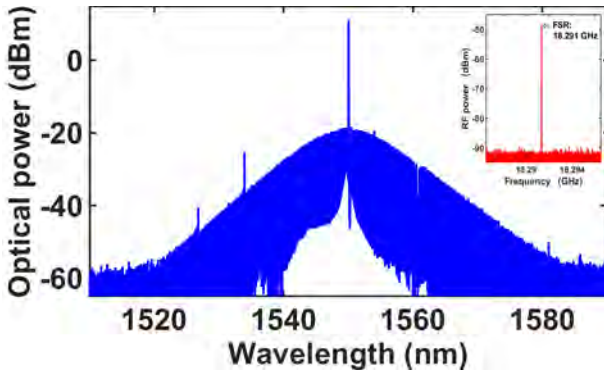


Fig. 2: Wavelength and RF spectra (inset) of the entire generated soliton comb. Since the pulse repetition rate was 18.29 GHz, the interval between the wavelength components was approximately 0.15 nm.

From the RF spectra, the pulse repetition rate of the soliton comb was found to be about 18.29 GHz, from which we can calculate that the wavelength spacing of the lines (= spacing of WDM carriers) was about 0.15 nm. Before inputting the soliton comb into the bandpass filter to extract the comb lines, only the pump light was removed by using a fiber Bragg grating (FBG).

The BER and eye diagrams obtained as a result of the transmission for the three comb lines with wavelengths close to 1,540 nm, 1,551 nm, and 1,554 nm, respectively, are shown below.

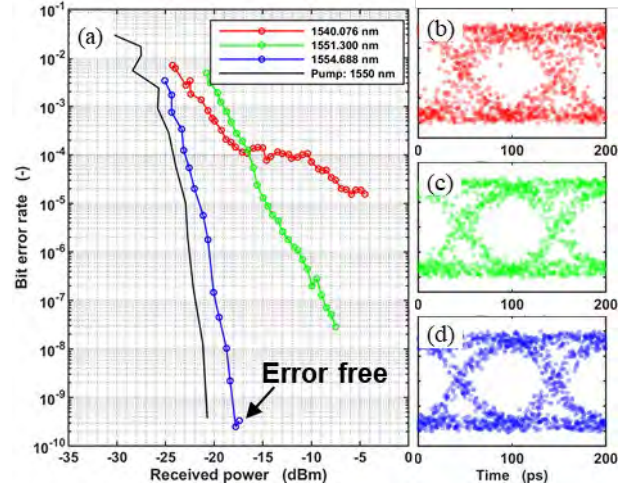


Fig. 3: BER obtained by transmitting three comb lines with different wavelengths (a) and the corresponding eye diagrams (b-d). Error-free transmission was achieved for the comb line with the wavelength indicated in blue. The black line is the BER measured back-to-back with the pump light for reference (the modulated light was directly input to the receiver without the 40 km transmission line). The transmission characteristics of the comb will not be better than this (locating on the low power side).

Error-free transmission was achieved by transmitting the comb line with a wavelength of approximately 1,554 nm, shown in blue in the figure. On the other hand, the BER of the comb line with a wavelength of 1,540 nm (red) stopped at around 10^{-5} , indicating that the transmission characteristics were poor. The eye diagrams of the two comb lines also show clear differences. The BER of these three components was also measured for the four surrounding comb lines. However, we did not measure the power monitor using an attenuator, and only the best BER values of each component were obtained. The results are shown in Fig. 4 below.

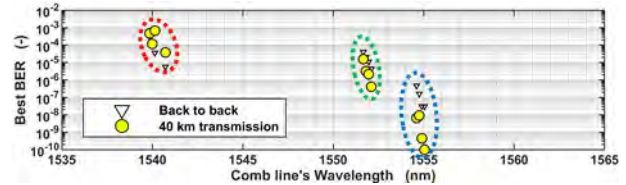


Fig. 4: The best BER of the three comb lines with different wavelengths and the four comb lines around each of them shows that they are all distributed together.

In addition to the blue comb line in Fig. 3, the neighboring components are predicted to achieve error-free transmission. However, although we tried to measure the best BER for all the comb components, we could not obtain the correct value, probably due to the problem of the experimental setup. We used a polarization-maintaining EDFA to amplify the comb component, but because we mixed it with a single-mode fiber, the polarization rotated and deviated from the fast/slow axis of its PM fiber, causing the gain to depend on the wavelength. As a result, it was not possible to determine how many comb lines could be used for error-free transmission. The investigation of the maximum number of available components and the calculation of the maximum spectral efficiency are the subjects of the next study.

Since the BER is uniquely determined by the signal-to-noise ratio (SNR) of the carrier, the transmission characteristics will vary depending on the original SNR of the comb line, even if it is amplified by EDFA. In fact, the spectrum in Fig. 2 shows a power difference of about 10 dBm between the wavelengths of 1,540 nm and 1,554 nm, which can be assumed to be the difference in transmission characteristics between the two comb lines. On the other hand, the comb line at 1,551 nm (green in Fig. 3), which should have higher power than blue, does not show error-free transmission. This may be because the amplified spontaneous emission (ASE) noise associated with the amplification of the EDFA contributes to the extracted comb line, which in turn degrades the SNR. The spectral envelope of the soliton comb has the shape of sech^2 , and the components with wavelengths closer to the pump light have higher power, but at the same time, the ASE noise becomes non-negligible. As a result, it is known that the transmission characteristics of the comb components in the immediate vicinity of the pump light are extremely deteriorated [13]. However, it is possible that the problem with the experimental setup described above affects the wavelength around 1,551 nm, so it is necessary to conduct measurements again after improving the experimental system.

4. Conclusion

Soliton combs based on MgF_2 microresonators have the potential to achieve high spectral efficiency by densely utilizing wavelength carriers in WDM transmission.

In this study, we performed WDM communication experiments using the IM-DD method on a soliton comb generated from an MgF_2 microresonator and measured the transmission characteristics. We transmitted three representative soliton comb lines with wavelengths close to 1,540 nm, 1,551 nm, and 1,554 nm, and demonstrated error-free transmission when the comb with a wavelength of 1,554 nm was transmitted. It was also found that the transmission characteristics of BER and eye diagram were different for each of them. The difference in characteristics between the combs at 1,540 nm and 1,554 nm is thought to be due to the original optical power (corresponding to SNR). The difference in characteristics between the combs at 1,551 nm and 1,554 nm is probably due to the contribution of ASE noise near the pump light, which also affects the SNR. On the other hand, there may have been a problem in the experimental system regarding polarization, and the amplification of each comb line may not have been sufficiently achieved. Although we were unable to determine the number of combs for error-free transmission, we were able to demonstrate the potential of the MgF_2 microresonator for communication applications.

Our future goal is to improve the problems in the experimental system described above, and then measure the BER again to determine the total number of comb lines that achieve error-free transmission (or to obtain the conditions). Furthermore, from the results, the spectral efficiency should be calculated and compared with previous studies and other studies.

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Fabrication of low-loss ring resonator by using Hot-wire CVD based thick SiN films

Koichiro Handa (M2) Shota Sota (M1)

We fabricated SiN microresonators with Hot-wire CVD thick SiN films (> 750 nm) by CMOS compatible process. Microresonators exhibiting their FSR ~ 400 GHz and quality factor as high as 1.96×10^5 were successfully demonstrated in the telecommunication L band. Furthermore, we fabricated an input/output tapered structure with a high aspect ratio (~ 8). Coupling efficiency of 30 % was achieved and a transition of a resonant wavelength (> 2.4 nm) due to thermo-optic effect was demonstrated.

Key words: Optical microresonator, Silicon nitride, low-temperature CVD process

1. Background

Silicon nitride (SiN) is a CMOS compatible material and transparent in visible to near-infrared wavelength range and it offers a useful platform that serves as wideband, low-loss optical integrated devices. However, since SiN exhibits normal dispersion in the telecommunication band, a film thickness more than 700 nm is required with SiO₂ cladding to obtain anomalous dispersion [1]. Since thermal expansion coefficient of SiN is larger than that of Si substrate, a large tensile stress is applied to the SiN film deposited by high temperature (~ 750 °C) CVD process. Especially in the case of thick SiN film (> 500 nm), it causes deterioration of the yield of the fabrication process. Considering the problem of such residual stress and future integration, 400 °C or less temperature is preferable for SiN deposition. However, in such a low-temperature deposited SiN film, substantial absorption due to the overtones of N-H (3350 cm⁻¹) and Si-H (2160 cm⁻¹) stretching modes become an issue [2]. SiN films deposited by Hot-wire CVD method was reported to have a lower residual hydrogen content in the films than that of plasma CVD method, which is one of the low-temperature CVD method [3], and is expected to realize low-loss dispersion-controlled devices in the telecommunication band [4]. In this report, SiN microresonator with Hot-wire CVD thick SiN films (> 750 nm) was fabricated by CMOS compatible process and its optical characteristics were evaluated.

2. Fabrication process of SiN microresonators

A hot-wire CVD SiN film was deposited on a Si wafers with thick thermal oxide film. SiH₄ and NH₃ were used as precursors with their flow rates fixed to 2.4 sccm and 80 sccm, respectively, at the deposition pressure of 4 Pa. Tungsten wires were electrically heated at 400 °C and were placed 15 cm beneath the wafers. When 600 W of a DC electric power was applied to the wires, the deposition rate reached to 6.3 nm/min. The film thickness and refractive index of the SiN film was measured to be 750 nm and 2.11 at 632.8 nm, respectively. To fabricate the device structures, a negative resist mask was first formed by using electron beam lithography followed by a reflow process. Then, the SiN layer was etched by a short-time ICP dry etching of CHF₃/Ar gas mixture and ICP cryogenic dry etching of SF₆/O₂. A narrow gap (< 400 nm) between the ring and the bus waveguide was embedded by SOG (spin on glass) and a TEOS-SiO₂ film (2 μ m thick) was deposited as the upper clad. Finally, the end facet was refined by dicing process.

3. Optical properties of SiN microresonators

For the evaluation of the optical characteristics of SiN microresonators, a CW (continuous wave) laser source was launched from one of the end facets via a lensed fiber and the output transmitted power was measured while scanning the laser wavelength. By measuring the half width of the transmitted power, quality factor was gained. Figure 1 shows the transmission spectrum of a microresonator with a waveguide width of 1.7 μ m and a ring radius of 57 μ m (FSR ~ 403 GHz) as an example of characteristics of the fabricated device. Quality factor as high as $Q_L \sim 1.96 \times 10^5$ was obtained near the critical coupling condition in the telecommunication L band.

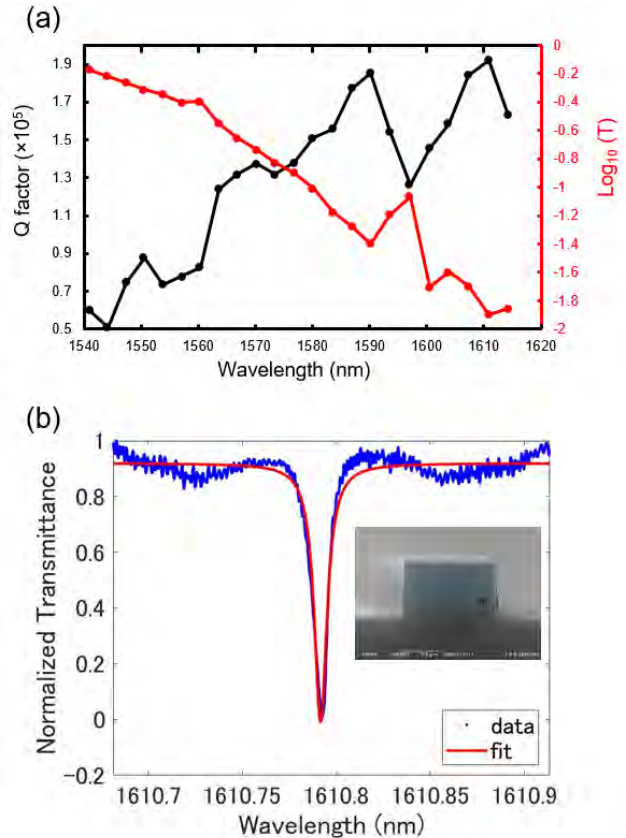


Fig. 1: (a) Waveguide dependence of the quality factor and transmittance of the fabricated microresonator. (b) Example of the resonance peak spectrum. Inset shows the SEM image of the waveguide structure.

4. High power optical input

To enhance coupling efficiency, it is important to fabricate an input/output tapered structure (width of 150 nm). For fabricating a tapered structure with a high aspect ratio (~ 8), a square box ($2\ \mu\text{m} \times 2\ \mu\text{m}$) as shown in Fig. 2(a) was introduced at the tip of the tapered structure. As a result, as shown in Fig 2(b), tapered structure (width of 157 nm) was successfully fabricated. With this tapered structure, a strong excitation light was input to a microresonator with a waveguide width of $1.7\ \mu\text{m}$ and a ring radius of $57\ \mu\text{m}$, as shown in Fig. 2(c). The power (mW) described in Fig. 2(c) means the output power at the waveguide end facet. With a coupling efficiency more than 30 %, a resonance shift (up to 2.4 nm) due to thermo-optic effect was confirmed, demonstrating the effectiveness of the tapered structure.

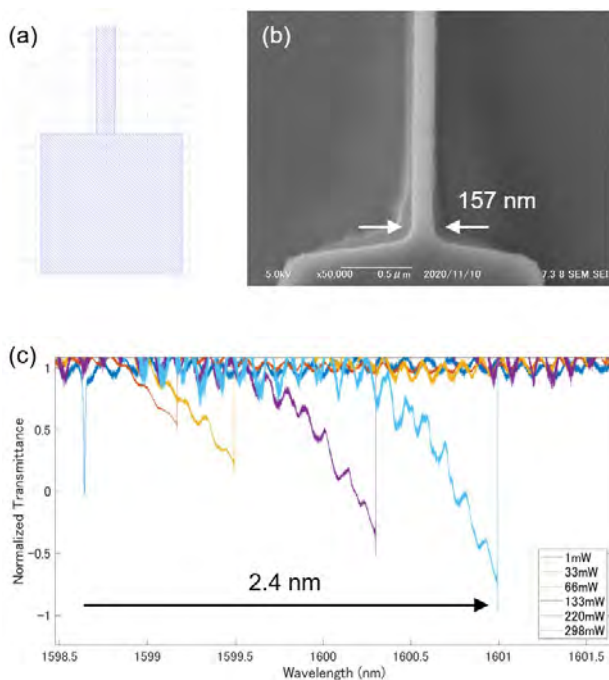


Fig. 2: (a) A square box introduced at the tip of the tapered structure. (b) Fabricated tapered structure. (c) Resonance shift by high power optical input.

4. Summary and outlook

We fabricated SiN microresonators with Hot-wire CVD thick SiN films ($> 750\ \text{nm}$) by CMOS compatible process. SiN microresonators exhibiting their FSR $\sim 403\ \text{GHz}$ and quality factor as high as 1.96×10^5 were successfully demonstrated in the telecommunication L band. To improve the optical coupling efficiency, an input/output tapered structure was fabricated and high-power intensity of light was input. A resonance shift up to 2.4 nm due to thermo-optic effect was confirmed with a coupling efficiency of more than 30 %.

Future outlook for SiN microresonator fabrication is further improvement of the quality factor and optimization of the input/output tapered structure. Optimization of the waveguide surface roughness is needed to achieve high quality factor. As a method for reducing the loss factor of SiN top surface, the introduction of chemical mechanical polishing (CMP), which is the surface polishing method,

can be considered. Previous study [5] shows that CMP reduces the surface roughness and improves quality factor by about 1.73 times. It is also needed to reduce the hydrogen content in the SiN film after fabrication of the waveguide structure. Previous study [6] shows that residual hydrogen concentration decreased by post-annealing at $1000\ ^\circ\text{C}$ or higher and the density of N-H bonds was reduced to about half at around $1050\ ^\circ\text{C}$. As a result, light absorption near the wavelength of $1520\ \text{nm}$ by N-H bonds can be reduced and improvement of quality factor in the telecommunication C band can be expected. In case of optimization of tapered structure, previous study [7] shows that due to the mode mismatch, the coupling efficiency drops by 50 % compared with the optimum taper width even if the taper width is shortened by several tens of nanometers from the optimum width. Similarly, in case of SiN microresonator used in this report, the coupling efficiency can be expected to increase by optimizing the tapered structure such as shortening the taper width.

By further improvement of quality factor and optimization of the coupling efficiency, future task is to observe parametric oscillation by SiN microresonator (FSR $\sim 403\ \text{GHz}$, $Q_L \sim 5 \times 10^5$) at the low threshold excitation optical power (310 mW), shown in previous research [8].

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Soliton comb generation using SiN microresonator

Soma Kogure (B4)

Optical frequency combs generated in optical microresonators, or microcombs have revolutionized photonics. When a resonator is pumped in a particular way, soliton combs are generated. Comb lines are mode-locked and ultrashort optical pulse generation is possible. Here, generation of soliton comb is demonstrated using SiN microresonator.

Key words: Microresonator, Kerr comb, Soliton comb

1. Introduction

Optical frequency combs are light with equidistance frequency modes, and they are called so because the spectra are identical to hair combs. Existing optical frequency combs broaden its comb lines by using mode-locked laser with lengthy HNLF (Highly nonlinear fiber) or phase modulation of CW light with bulky electro-optic modulator, which make them unsuitable for space-sensitive application. Some alternatives with smaller footprint were desired and in 2007, the first microcomb was demonstrated using microresonator reducing overall size considerably[1]. The resonator is pumped by CW laser confining the light strongly enough to produce signal and idler sideband by four-wave mixing (FWM). Cascaded FWM eventually forms optical frequency comb spanning tens of terahertz. The only downside was that comb lines were noisy due to its chaotic state.

In 2014, a mode-locked soliton comb was reported[2]. The mechanism of microcomb is described by the Lugiato-Lefever equations and it shows that there are two conditions to meet for soliton comb generation. First, the cavity needs to exhibit anomalous dispersion where the free-spectral range (FSR) increases with the mode frequency. Second, the pump wavelength needs to be longer than the wavelength of the pumped resonance. This is described as “red-detuned”.

There are a few typical materials used for microresonator namely MgF_2 crystalline resonator, silica toroid resonator, and silicon nitride (SiN) microresonator. Since SiN can be found in many CMOS (Complementary Metal-Oxide-Semiconductor) process and thus chip integration is easy. Even though the minimum 700 nm of thickness for anomalous dispersion is a little bit challenging to process, its high nonlinearity and low-loss characteristics are advantageous.

Here, soliton comb generation is demonstrated using SiN microresonator. To do so, fast scan technique is implemented[3].

2. Method of soliton comb generation

The first platform for soliton comb generation was MgF_2 crystalline resonator. Intracavity power and heat shifts the resonance wavelength to red side because of the Kerr effect and the thermal effect. To transit to red-detuned regime, the pump light was scanned from blue side to red side. Fig. 1 shows the intracavity power when detuning changes. As soon as soliton comb is generated, the intracavity power decreases suddenly and soliton step can be observed. At the same time resonator is cooled shifting the resonance and consequently soliton regime is lost. Optimized laser sweeping rate prevents the cooling, as the cavity is in thermal equilibrium when sweeping is over.

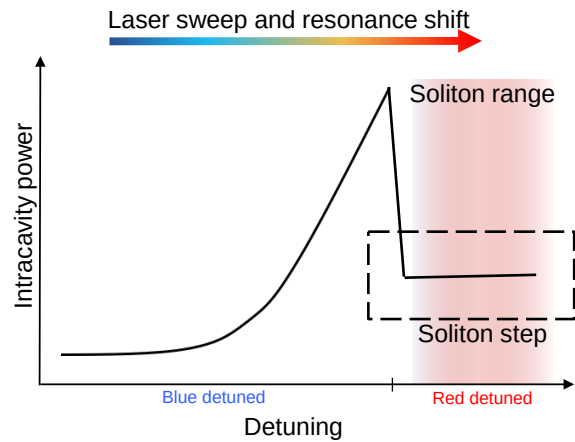


Fig. 1: As the pump laser is swept, the intracavity power increases and the resonance shifts toward red side. In red-detuned regime, step-like pattern appears.

However, one red-detuned regime is not accessible with SiN resonator using the same sweeping technique. Normalized thermo-optical effect coefficient, $(n^{-1}dn/dT)$ indicates dependence of refractive index on temperature. SiN ($30 \times 10^{-6} \text{ K}^{-1}$) is much more sensitive to temperature change compared to MgF_2 ($0.6 \times 10^{-6} \text{ K}^{-1}$). Resonator would never be in thermal equilibrium when sweeping is over. That is why fast scan technique was invented. Instead of slow piezo tuning, Single-sideband (SSB) modulator shifts the pump light frequency for faster scan.

Simplified experimental setup is shown in Fig. 2. The wavelength shift of the light from SSB modulator is determined by the input RF frequency for VCO. The RF frequency is set by the input voltage of VC, so generating ramp waveform from FG can shift the wavelength of the output light. The rate of sweeping is ~ 10 GHz/ μ s in fast scan technique rather than ~ 10 kHz/ μ s in MgF₂ resonator.

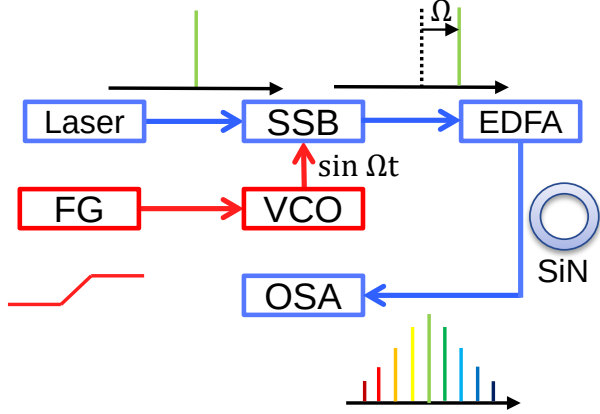


Fig. 2: Experimental setup for fast scan technique. SSB; Single sideband modulator, EDFA; Erbium doped fiber amplifier, OSA; Optical spectrum analyzer, VCO; Voltage controlled oscillator, FG; Function generator

3. Results

The resonator was fabricated by Ligentec. The resonator radius is 50 μ m, FSR is 400 GHz. The thickness of waveguide is 800 nm, the width is 1.6 μ m. It is confirmed that this resonator exhibits anomalous dispersion by numerical simulation. The measured Q factor of the resonator is shown in Fig. 3.

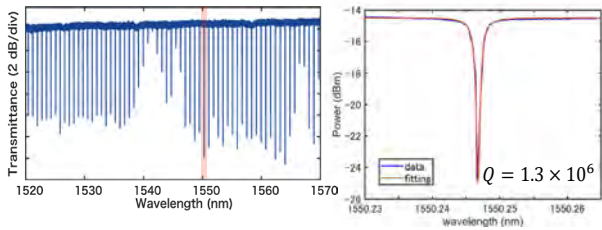


Fig. 3: Measured spectrum of the resonator. The pumped mode is shown.

The Q factor was 1.3×10^6 . Since the soliton range is proportional to the input power, the output of EDFA is ~ 1 W. When sweeping is insufficient, the pump light remains in the blue-detuned regime. As Fig. 4 shows, Turing pattern comb and modulation instability comb is generated.

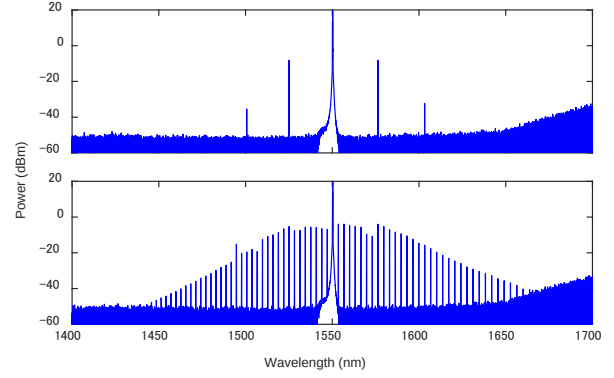


Fig. 4: (a) The spectrum of Turing pattern comb. (b) The spectrum of modulation instability comb.

As the ramp waveform of FG is adjusted, Soliton steps get longer and longer. At first the step was a few hundreds ns long, but eventually a few ms of step began to appear. Fig. 5 shows the spectrum of soliton comb. It was stable and lasted for more than 10 minutes.

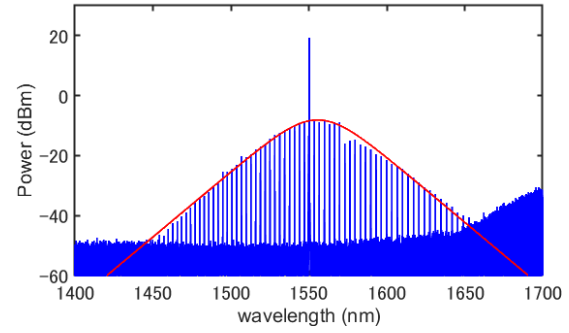


Fig. 5: The spectrum of soliton comb.

4. Conclusion

In this work, soliton comb generation was demonstrated using SiN microresonator with FSR 400 GHz. To overcome the thermal dependence, fast scan technique was implemented. Soliton comb was stable for over 10 minutes thanks to its self-stability.

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Microresonator-based microcomb for WDM transmission

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Microcomb is generated by four wave mixing, which is one of the nonlinear optical effects, and has higher repetition rate, higher integration, and lower power consumption than conventional optical frequency combs using mode-locked lasers. The principle of microcomb has been elucidated, and applications of microcomb have begun to be devised and demonstrated. In this study, I have focused on the multi-wavelength nature of microcomb and studied their application to optical communications. Wavelength division multiplexing (WDM) transmission using intensity modulation - direct detection (IMDD) method was then performed for the microcombs obtained using silicon nitride microresonator under two conditions: back-to-back and 40 km. The microcomb transitions to various states by changing the detuning, which is the difference between the resonance wavelength and the pump wavelength, and shows different transmission characteristics in each state.

Key words: Microresonator; Microcomb; Soliton comb; Optical communication

1. Background

Microcomb, which are optical frequency combs generated using microresonators, were reported in 2007. Since then, the research of microcomb has been greatly developed and various applications have been proposed [1]. In this study, we investigated the application of microcomb to WDM (Wavelength Division Multiplexing) optical communications.

In WDM communication, the wavelength and frequency used for transmission are specified by the International Telecommunication Union. Therefore, it is necessary to prepare DFB lasers for each specified wavelength, which is undesirable for increasing the capacity of communication. As the number of communication channels increases, the number of DFB lasers required increases, which in turn increases the cost and power consumption. This problem can be solved by using a microcomb light source. The microcomb light source can cover a wide wavelength band from a single CW light source without any problem due to the increase in the number of channels, and is expected to be a breakthrough from the conventional WDM communication system.

2. Microcomb generation

Microcomb is generated by injecting high-intensity light into a silicon-nitride microresonator and sweeping the wavelength. Here, the microcomb is generated by amplifying the light from a tunable laser using an Erbium Doped Fiber Amplifier (EDFA) and inputting it into the microresonator. The generated microcomb was observed using an optical spectrum analyzer (OSA), and the results are shown in Fig.1. The transitions in the microcomb is generated by

changing the detuning, which is the difference between the laser wavelength and the resonance wavelength. The microcomb state transitions associated with the detuning change are referred to as "Turing pattern", "Modulation Instability phase I", and "Modulation Instability phase II" in this research. The first microcomb generated when the laser beam is input to the resonance is the "Turing pattern". After the "Turing pattern" is generated, the laser is swept to the long wavelength side, which increases the power entering the cavity and further generates four-light wave mixing. The resulting microcomb is called "Modulation Instability phase I". The microcomb generated by further wavelength sweeping is "Modulation Instability phase II".

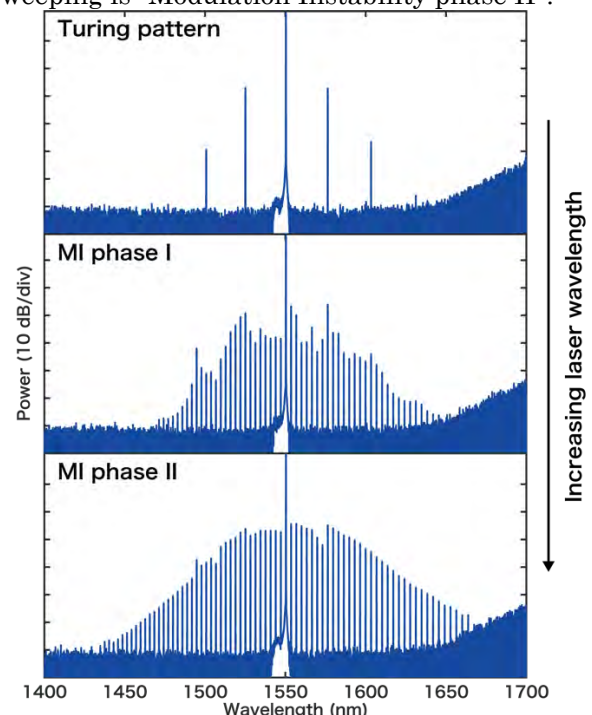


Fig. 1: Transition of microcomb state with wavelength change of laser light.

A mode-locked soliton comb was reported in 2013 [2]. In this research, it was generated by using a method called fast scan, which is a fast sweep of the laser wavelength.

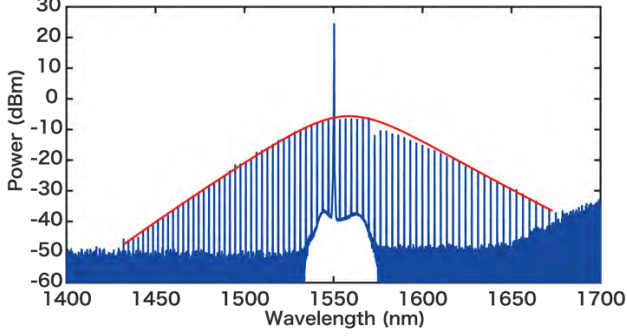


Fig. 2: Soliton comb generated using fast scan.

3. Microcomb transmission

Transmission experiments were conducted using four types of microcomb. The three types of microcomb, "Turing pattern", "Modulation Instability phase I", and "Modulation Instability phase II", used three comb lines of 1525.2 nm, 1550.3 nm, and 1576.5 nm. Soliton comb used 9 comb line on the long wavelength side from the pump light at 1525.2 nm. The results of each transmission characteristic are shown in Figures 3 and 4.

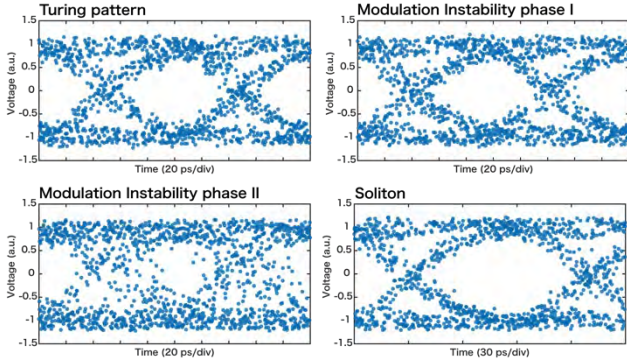


Fig. 3: Transmission characteristic results of 4 types of microcomb (eye pattern).

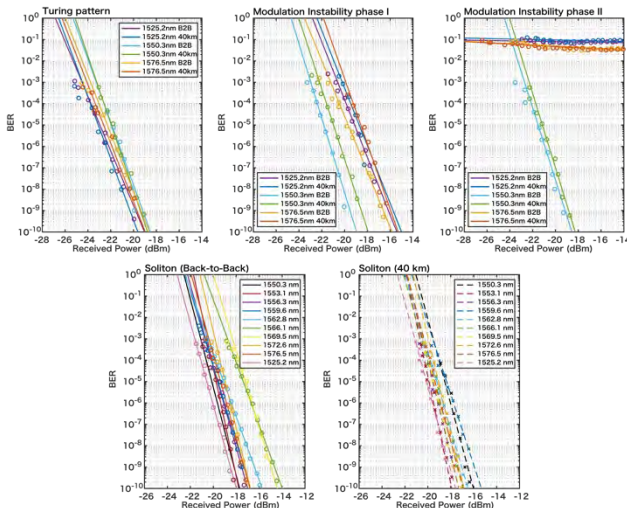


Fig. 4: Transmission characteristic results of 4 types of microcomb (Bit Error Rate).

The transmission characteristics showed different results depending on the state of the microcomb. As the transition from "Turing pattern" to "Modulation Instability phase II" progresses, the transmission characteristics of Soliton comb deteriorate. All comb lines can observe bit error rates of 10^{-10} , and the transmission characteristics are very good. It became. Although 10^{-10} can be observed in other microcomb states, there are few comb lines that can be used, and it is considered that Soliton comb is the most suitable for the optical communication application of microcomb.

4. Microcomb noise

To investigate the cause of the difference in transmission characteristics depending on the state of the microcomb, the beat noise and relative intensity noise of the microcomb were measured. The results are shown in Figures 5 and 6.

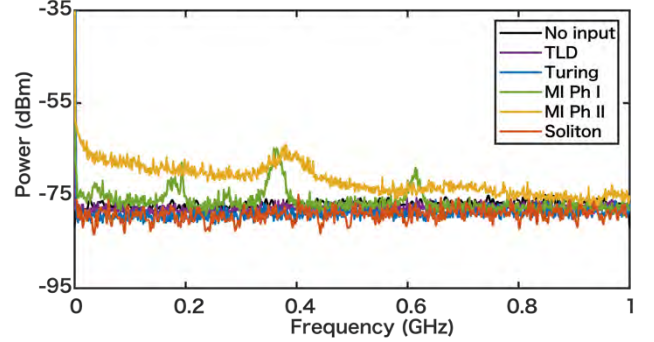


Fig. 5: 4 types of microcomb beat noise

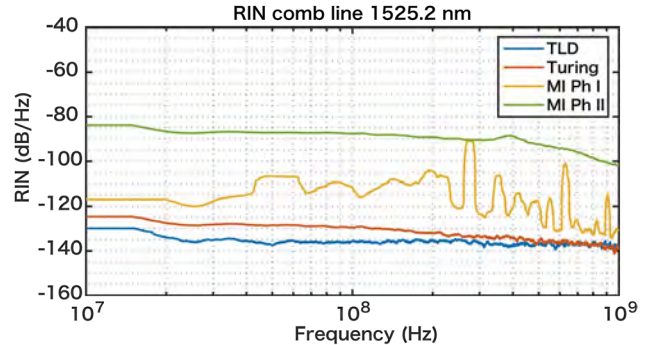


Fig. 6: Relative intensity noise of microcomb.

The noise of each microcomb was different depending on the state. "Modulation Instability phase II" has very poor noise characteristics. It is considered that the transmission characteristics are changed by such noise. From the above results, it is necessary to select a suitable microcomb when applying microcomb to optical communication.

5. Conclusion

Transmission experiments with microcomb using silicon nitride microresonators were carried out. The transmission characteristics obtained were different depending on the state of the microcomb.

In the transition from the "Turing pattern" to the "Modulation Instability phase II", the transmission characteristics changed very poorly. The measurement of the noise of the microcomb showed that the noise characteristics were also poor. From the above results, it is necessary to select a suitable state of microcomb for optical communication, and among the four types of microcomb used in this study, the soliton comb is the most suitable for optical communication.

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Raman comb transmission using microcavities

Shuto Sugawara(B4)

The transmission using a silica microcavity with a Raman comb was performed. A bit error rate (BER) = 10^{-4} was achieved by transmission using a single Raman comb. In this study, a Raman comb was generated at 1570 nm by using continuous wave in the S-band for excitation, and the transmission could be carried out using conventional transmission equipment.

Key words: Microcavity; Silica; Raman comb

1. Introduction

The optical frequency comb is a light with a precisely spaced frequency spectrum, and its name comes from the fact that the frequency spectrum looks like a comb. Optical frequency comb has a wide range of applications, including use as a measure on the frequency axis [1] and as a light source for communication.[2]

One method of generating an optical frequency comb is to use a microcavity [3]. Microcavities have attracted much attention in recent years because of their relatively high Q-values, which indicate their ability to confine light, and their small mode volumes, which are the areas where light is confined. The optical frequency comb generated by using a microcavity is also called a microcomb. Microcombs are expected to be smaller, cheaper, and more energy efficient than conventional optical frequency combs using ultrashort mode-locked lasers.

Conventional microcombs are generated by four wave mixing, a kind of third-order nonlinear optical Kerr effect, and are also called optical Kerr combs. There are several types of optical Kerr combs, but all of them have disadvantages such as large noise and complicated generation procedures. In addition to the optical curvature effect, there are other types of microcombs such as Raman combs generated by induced Raman scattering. However, the Raman comb has not been studied yet and there are still many unknowns.

In this paper, we report on transmission experiments using Raman comb. The performance of the Raman comb in transmission was confirmed, and the possibility of the application of the Raman comb to transmission was confirmed.

2. Silica microsphere resonator

In this experiment, a silica microsphere resonator was used. Silica can generate Raman combs with a wide bandwidth because the characteristic function of induced Raman scattering is relatively widely distributed on the frequency axis. In addition, the microsphere resonator is suitable for observing nonlinear optical effects because it has both a high Q value

and a small mode volume. The silica microsphere resonator is shown in Figure 1. Figure 1(a) shows the resonator taken through a microscope. Figure 1(b) shows the measurement results of the Q value. The Q value of the resonator used in this experiment was $Q=4.37 \times 10^7$.

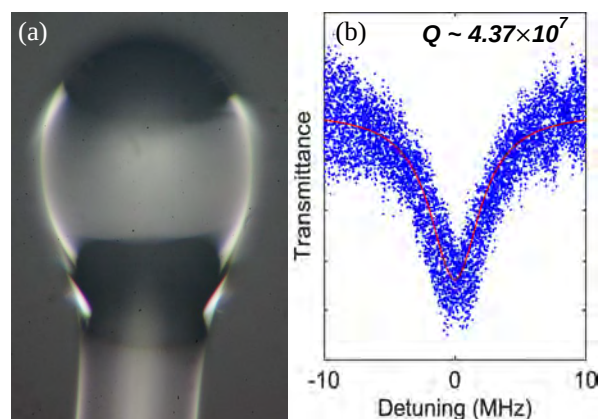


Fig. 1: The silica microsphere resonator used in this experiment. (b) The result of Q measurements of the silica microsphere resonator. $Q = 4.37 \times 10^7$ was calculated.

3. Transmission experience

The silica microsphere resonator described above was used to generate a Raman comb for transmission experiments. The experimental setup is shown in Figure 2 (a). In this experiment, an intensity modulator was used as the transmitter and transmission was performed using an intensity modulation method. A square wave was input to the modulator by a pulse pattern generator. The data rate was set to 10 GHz. The transmission path can be changed by a switch between back-to-back (B2B), which directly connects the transmitter and receiver, and 40 km. Figure 2(b) shows the spectrum of the Raman comb after it was generated. 13 dBm intensity continuous light with a frequency of 1480.6 nm, amplified by an S-band optical amplifier, was injected into the resonator as a pump to generate the Raman comb. The pedestal-like spectrum seen near the pump light is the ASE noise caused by the S-band amplifier. A comb is also generated near the pump light, which is an optical Kerr comb generated by four-wave mixing. The Raman comb

was generated in the band from 1550 nm to 1610 nm. The comb at 1570.9 nm, which had the highest intensity among the generated Raman combs, was selected as the transmission light source and cut out using a bandpass filter.

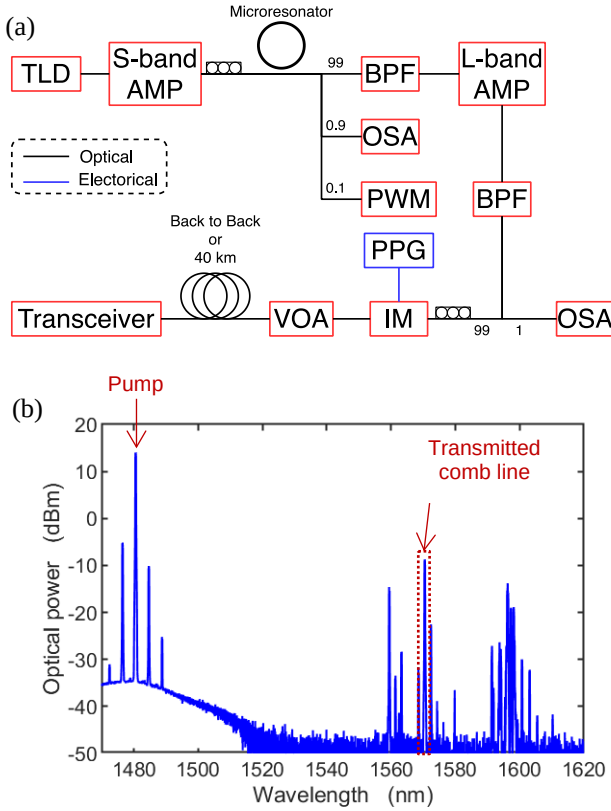


Fig. 2: (a) Schematic experimental setup of the transmission experiment using Raman comb. (b) Spectrum of the pump light and the generated Raman comb.

Figure 3 shows the results of transmission of the cut-out combs. Figure 3(a) shows the measured BER. The green triangle shows the B2B results, and the red circle shows the 40 km transmission results. On the other hand, in the 40 km transmission, the minimum BER is about 10^{-6} , but the blurring is very large. However, when the received power is above -15 dBm, the BER is suppressed to a maximum of about 10^{-3} . Figures 3(b) and 3(c) show the eye patterns for B2B and 40 km transmissions, respectively. In both cases, it can be confirmed that the eye is open, but the lines are thicker, and the noise is larger. In particular, Figure 3(c) shows that there is also a dot in the center of the eye, indicating that the noise is large.

4. Conclusion

The transmission using Raman comb with silica microsphere resonator was successfully demonstrated. The BER of the transmission characteristics of the Raman comb was found to have a floor at 10^{-4} . The cause of this floor is thought to be the noise peculiar to the Raman comb, but the reason is not clear. Therefore, the

future task is to evaluate the noise peculiar to Raman comb and to reduce the floor of BER.

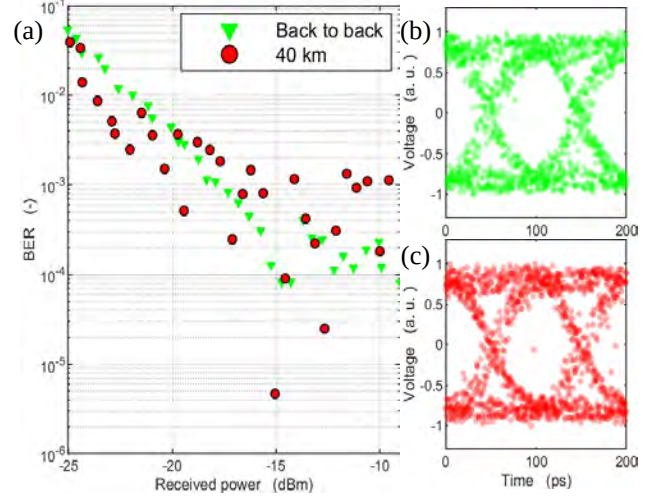


Fig. 3: The results of Raman comb experiment. (a) BER of B2B and 40 km transmission. (b) Eye patterns of B2B and 40 km transmission, respectively.

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Fabrication and optical properties of high gain Er-doped microcavity

Riku Imamura (M2)

A microresonator-based mode-locked laser has a high pulse repetition rate. There is the possibility of realizing a passive mode-locked laser with CNTs as a saturable absorber and an erbium-doped microresonator. In this work, we proposed a new fabrication method for Er-doped toroidal cavities and evaluated the optical properties, such as gain per roundtrip and resonator dispersion.

Keyword: Microresonator, Erbium-doped device, Sol-gel method, Mode-locked laser

1. Background

Fiber-based mode-locked (ML) lasers provide high performance while being relatively inexpensive. The generation of high-repetition-rate pulses is gaining interest, but it remains a challenge to achieve a GHz repetition rate with fiber lasers because of their long cavity length. On the other hand, whispering-gallery-mode (WGM) microresonators allow the strong confinement of light and miniaturizing an ML laser into a WGM microresonator will enable us to achieve a high repetition rate, a small footprint and on-chip integrability. We explore the possibility of realizing a passive ML laser with the system shown in Fig. 1. There are two key technologies involved; one is saturable absorption (SA) and the other is laser gain in a microresonator. We selected a carbon nanotube (CNT) as a saturable absorber and erbium as the laser gain medium. Our group demonstrated SA in a microresonator experimentally by growing CNTs selectively on a silica microtoroid by chemical vapor deposition. By performing a pump-probe-like experiment we successfully characterized the SA behavior in a microresonator system. This is the first demonstration of SA in a WGM microcavity system^[1].

In this study, we then fabricated an active erbium doped microtoroid by using sol-gel method. The numerical analysis shows that the dispersion of the resonator is important to achieve the mode-locking as well as the soliton generation by the usual WGM resonator. Therefore, it is necessary to control the dispersion, that is, to change the diameter of the resonator. However, the conventional fabrication method of Er-doped toroids makes it difficult to enlarge the diameter, so a new fabrication method was employed to fabricate Er-doped toroidal resonators with an expanded resonator diameter.



Fig. 1. A schematic illustration of a mode-locked laser with CNTs and an Er-doped microresonator.

2. Fabrication of Er-doped microtoroids using a new method

In the conventional fabrication method of Er-doped microtoroid, at first, an Er-doped sol-gel silica film is deposited on a silicon substrate, and then the microtoroid is fabricated using the same fabrication method as for general silica microtoroids^[2]. However, it is difficult to increase the resonator diameter using this conventional method. The biggest reason for this is the fabrication problem, because the expansion of the resonator diameter causes the disk to distort. This phenomenon is known as “buckling,” in which the silica disk is distorted due to the difference in the thermal expansion coefficients of the silica and silicon, and it is a factor that reduces the *Q* value of the resonator^[3]. Therefore, the thickness of the film that can be formed by the sol-gel method is about 2 μm , which limits the diameter of the film to about 100 μm in the conventional method.

The thickness of the silica film is important for the buckling, and in order to fabricate a resonator with a target diameter of 500 μm ~ 1 mm, a silica film thickness of about 8 μm is required. Therefore, we changed the process of using the sol-gel method as shown in Fig. 2. We fabricated a disk resonator as a supporting material from a thermally grown silica film with a thickness (8 μm) that does not distort even when the resonator diameter is large, and sol-gel coated it to fabricate an Er-doped toroid without distortion. The method of spin-coating the disk resonator with a sol-gel solution and reflow is a new technique that has not been employed before.

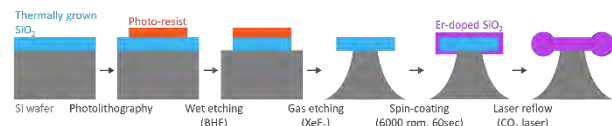


Fig. 2. Fabrication flow of Er-doped toroidal resonators using the coating method. Erbium ions are doped into the silica disk resonator by coating with a sol-gel solution.

Using this fabrication method, an Er-doped disk resonator with a diameter of 600 μm was coated with an Er-doped sol-gel film thickness of about 300 nm (Fig. 3(b)), and after CO_2 laser reflow, an Er-doped toroidal resonator with a diameter of 450 μm was fabricated (Fig. 3(c)). In addition, defect-free coating was achieved by maintaining the atmosphere in the spin coater at ethanol, the solvent of the sol-gel solution (Fig. 3(a)).

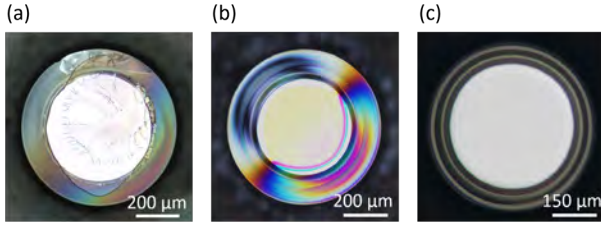


Fig. 3. (a) A microscopic image of cracks in the silica disk area caused by coating under inappropriate conditions (diameter: 600 μm). (b) A microscopic image of disk resonator with defect-free sol-gel coating. The Q factor was 1.2×10^6 before and after the coating process (diameter: 600 μm). (c) A microscopic image of Er-doped toroidal resonator with diameter of 450 μm fabricated by laser reflow of disk resonator.

3. Optical properties

Here we describe the optical properties of an Er-doped toroidal resonator with an enlarged resonator diameter using a coating method. The diameter calculated from microscopy and FSR spacing is 450 μm , which is, to the best of our knowledge, the largest diameter among the Er-doped toroidal resonators reported. The Q -value in the pumping mode around 1480 nm is 3.5×10^6 , and single- and multimode laser emission is observed around 1550 nm (Fig. 4(a)). The laser threshold was 350 $\mu\text{W} \sim 400 \mu\text{W}$, and the lasing efficiency was 1.5%. The problem with this coating method is that it is difficult to estimate the Er ion concentration. In the coating method, as shown in Fig. 4(b), thermally grown silica and Er-doped sol-gel silica are mixed during CO_2 laser reflow. Therefore, in this study, the doping concentration was calculated from the lasing efficiency. In addition, the gain per roundtrip of the resonator was calculated from the doping concentration.

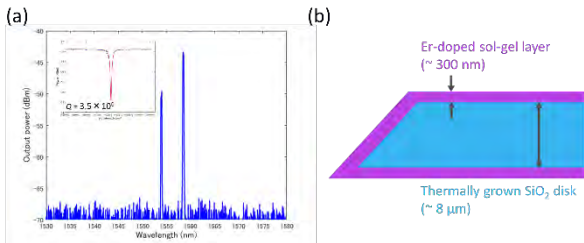


Fig. 4. (a) Er-doped toroidal cavity with diameter of 450 μm lased around 1550 nm when pumped at 1480 nm. (b) A schematic illustration of sol-gel coated before laser reflow. The thicknesses of thermally grown silica as a support material was 8 μm and sol-gel coated film was about 300 nm, respectively.

The determination of the Er doping concentration from the experimentally measured lasing efficiency has been investigated in a previous study by B. Min, *et al.* [4]. The calculations can be performed by using the coupled mode theory, the rate equation, and the relationship between absorption and emission of Er ions. Fig. 5(a) shows the relationship between the lasing efficiency and the Er doping concentration at different coupling coefficient κ . The Er doping concentration could be calculated from the lasing efficiency and the experimental conditions, and the doping concentration of the fabricated resonator was determined to be $1.5 \times 10^{19} \text{ cm}^{-3}$. By analyzing the rate

equation, as shown in Fig. 5(b), the relationship between the gain per resonator roundtrip and the Er doping concentration was obtained, and the gain per roundtrip was 3.0×10^{-3} .

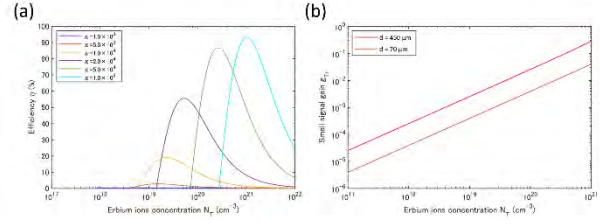


Fig. 5. (a) The relationship between erbium ion concentration and lasing efficiency at different coupling coefficients κ . (b) The relationship between erbium ion concentration and small signal gain per roundtrip at different diameter.

We also measured the dispersion in the Er-doped toroidal resonator. Fig. 6(a) shows the transmittance spectrum from 1545 nm to 1565 nm. The red circle is the fundamental mode, and the dispersion was calculated for this mode. In Fig. 6(b), the blue dots are the measured values, and the solid red line is the fitting curve of the fundamental mode including the third-order dispersion. The red dashed line is the theoretical curve of the dispersion of the silica toroid without Er doping and assuming a same structure. As a result of the measurement, it was found that the resonator dispersion shifted to the anomalous dispersion due to Er doping.

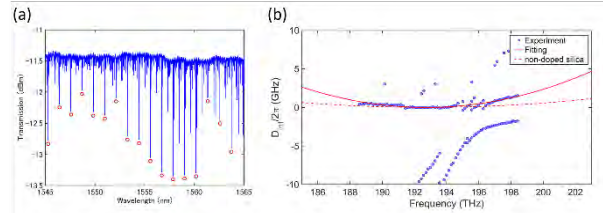


Fig. 6. (a) Transmission spectrum of an Er-doped toroidal resonator around 1550 nm. Red circles indicate the fundamental TE mode, for which dispersion measurements were calculated. (b) Blue dots represent measured dispersion of fundamental TE mode (red circles in (a)). The red line is the fitting curve for the measured dispersion. The red dashed line is the theoretical dispersion of the bare silica toroidal cavity that has equal major and minor diameters.

In conclusion, the fabrication and optical properties of Er-doped toroidal resonators are described. In particular, the Er ion doping method using the coating method is a new method, and it can be fabricated more quickly and easily than the conventional method. As for the optical properties, we evaluated the doping concentration and the gain per roundtrip from the lasing efficiency.

In the outlook for the future, we aim to achieve pulsed operation by controlling the dispersion of the Er-doped toroidal resonator based on numerical analysis and by achieving a high Q -value, as described in another report.

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Fabrication of high-Q silica rod resonator and development of a new reflow system

Shuto Sugawara (B4), Riku Imamura (M2)

Optical microresonators can enhance the light and matter interaction. In this study, we have developed a method to stably fabricate silica rod resonators with a high Q -value exceeding 10^7 , and developed a reflow system for toroidal resonators using a newly introduced CO₂ laser. In addition, future plans for improving the fabrication conditions of microtoroids are discussed.

Keyword: Microresonator, silica rod, silica toroid, CO₂ laser

1. Fabrication of rod resonators

The procedure for making silica rods is as follows.

1. Alignment of the creation system
2. Centering the silica rod
3. Create a resonator

Initially, I will explain the alignment of the creation system. First, the optical axis is set to pass perpendicular to the silica rod, and two irises are placed on the optical axis. The height of the optical axis should be slightly off the center of the silica rod. Remove the silica rod and ZnSe lens and adjust the angle and position of the mirror so that the alignment laser passes through the center of the irises. Finally, install the lens and adjust its position so that the laser passes through the center of the lens and irises.

Next, I will explain centering the silica rod. The silica rods are mounted on the spindle and rotated. However, the axis of the silica rods may be misaligned with the axis of rotation due to slanting during mounting. In order to solve this problem, the silica rods are irradiated with a CO₂ laser while being rotated and moved along the axis of rotation. In this way, the center axis of the silica rod can be aligned with the axis of rotation.

Finally, create the resonator on silica rod. This is done by digging two grooves in the silica rod, which is irradiated by the CO₂ laser while rotating the silica rod. The shape and characteristics of the resonator can be changed by the position of the ZnSe lens and silica rod, the power of the CO₂ laser, and the irradiation time.

It needs to be careful even after it is created. The dust generated during the creation process adheres to the surface, and if it is combined with the tapered fiber as it is, the Q -value will be low and the tapered fiber will become dirty. Therefore, it is necessary to remove the dust by blowing nitrogen on the surface after preparation.

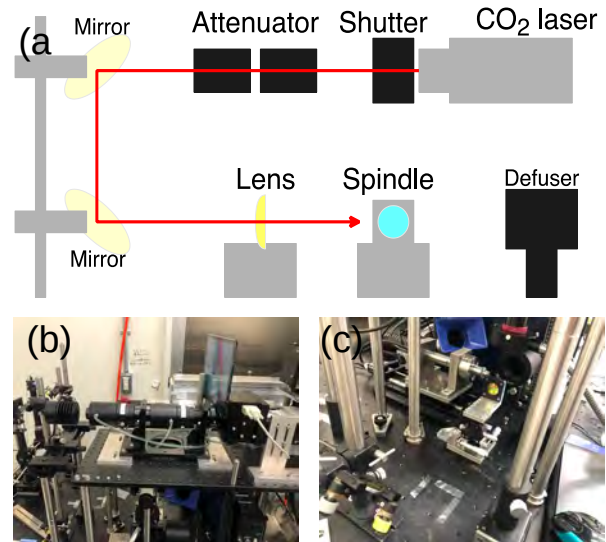


Fig. 1. (a) Schematic of silica rod creation system. (b) CO₂ laser used for silica rod creation. (c) Laser irradiation section.

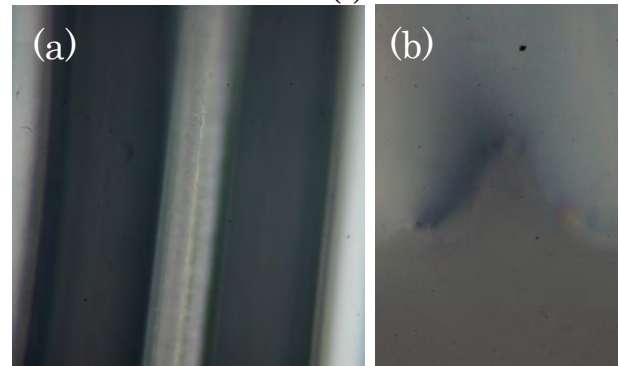


Fig. 2. Example of failure in silica rod preparation. (a) Rough surface does not allow light to couple. (b) The distance between the grooves is too close and the resonator is collapsed.

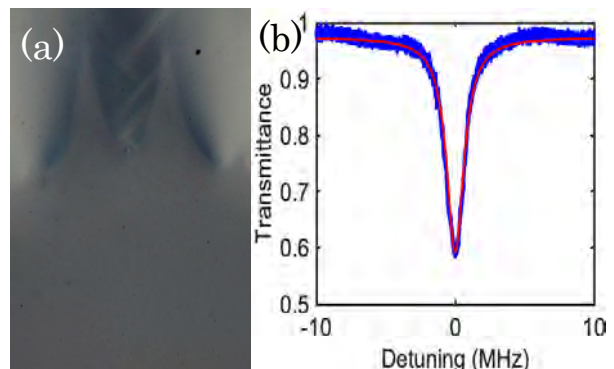


Fig. 3. (a) Created silica rod resonator. (b) Measurement result of Q -factor of the silica rod resonator. $Q = 1.32 \times 10^8$

2. Introduction of a new CO₂ laser

Until last year, the reflow of the toroidal resonator and the reflow of the rod resonator were fabricated using the same CO₂ laser. One of the problems associated with this was that the optical system had to be switched for each resonator to be fabricated. Since the fabrication conditions for each resonator changed each time, adjustment was required each time the resonator was used.

Therefore, the reflow system of the toroid and rod resonators was divided by introducing a new CO₂ laser. Since the maximum irradiation power of the conventional CO₂ laser (Coherent Diamond C-70L) was 70 W, it was installed for the rod resonator, which requires higher irradiation power, and the new laser was installed for the toroid resonator. The laser purchased was Access Laser's AL30, which was selected because of its circular beam profile and very small M² parameter of 1.1. The previous Coherent laser had an elliptical beam profile, which slightly distorted the rim of the toroidal cavity, and this was thought to be one of the factors that caused the Q value to decrease.

Since the old and new lasers are both water-cooled, the same chiller can be used for both lasers and two lasers were connected to the chiller in line. A schematic diagram is shown in Fig. 4. Then, the optical path length of the laser (Access Laser) was adjusted so that the spot size was about 400 μm in diameter.

as well. For these reasons, we plan to enclose the reflow system of the toroid resonator in an air barrier and purge it with nitrogen gas. As no major construction work is required, this project can be undertaken easily. The Q-value of the toroidal cavity was in the upper part of 10^6 when the previous laser (Coherent) was used, and it improved to the lower to middle part of 10^7 when the new laser (Access Laser) was used. However, the Q-values of other research groups are around 10^8 [1, 2], so we aim to raise the Q-value by fabricating the process in a clean environment.

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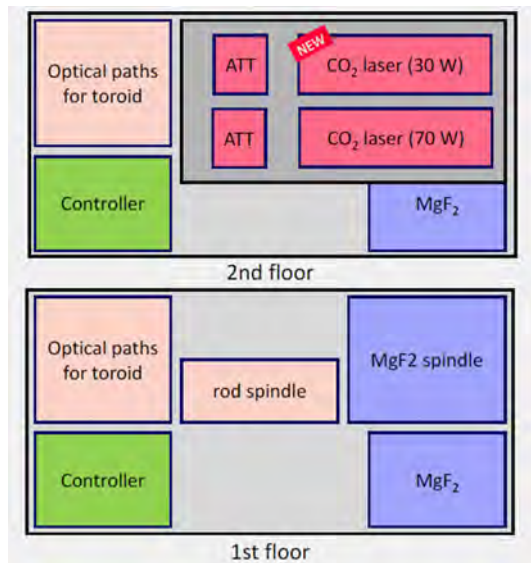


Fig. 4. A schematic illustration of the reflow system incorporating two CO₂ lasers. The two lasers were connected to the chiller in line.

3. Future Perspectives

As for future perspectives, it is necessary to solve the problem of fine dust on toroidal resonators, as was also a problem seen in rod resonators. In contrast to rod resonators, which have a relatively large diameter, toroid resonators are fragile due to their microstructure. Therefore, cleaning after the formation of the resonator structure is not possible, and all processes need to be kept clean. Since all the processes before laser reflow are performed in a clean room, the cleanliness should be maintained during reflow

Design of a passively mode-locked WGM microlaser with Er-doped microresonator and saturable absorber

Keigo Nagashima (M1)

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. Based on the experimentally determined gain of the Er-doped microresonator and the modulation depth of the CNT, the mode-locking condition was clarified by numerical analysis using the nonlinear Schrodinger equation.

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

1. Background

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

The aim of this study is to achieve passive mode-locking by adding Er to the gain medium, enabling self oscillation at 1550 nm with a pump light at 1480 nm, and by using the saturable absorption property of carbon nanotubes (CNT), which transmits light with high intensity and absorbs light with low intensity (Fig.1). In our laboratory, we have observed oscillation at around 1550 nm by injecting a pump light of 1480 nm into the Er-doped microresonator. We also observed the saturable absorption property of CNT by mixing CNT with PDMS and coating the toroidal resonator. However, we have not yet been able to confirm the mode-locking by combining them. Therefore, it is necessary to find appropriate values for each parameter, and numerical analysis was performed based on the experimentally obtained Er gain and the modulation depth of the CNT.

2. The gain of Er-doped microresonator

In our laboratory, Er-doped silica films were fabricated by the sol-gel method. Then, toroidal resonators were fabricated by photolithography, BHF etching, XeF2 etching, and laser reflow on the silica film. By injecting a pump light of 1480 nm into the Er-doped toroidal resonator, we observed oscillation at around 1550 nm. The results are shown in Fig. 2. The one shown in red

has an Er concentration of $1.7 \times 10^{18} \text{ cm}^{-3}$ in the starting solution, and the one in blue has an Er concentration of $0.85 \times 10^{18} \text{ cm}^{-3}$. The diameter of the resonator is about 70 μm in both cases, and the oscillation efficiency is 1% and 0.6%, respectively. The oscillation threshold is about 5 μW for both resonators. Fig.3 shows the effective Er concentration of this resonator when the mode overlap is assumed to be 100%. The horizontal axis of this graph represents the Er concentration per unit volume, and the vertical axis represents the oscillation efficiency, which is derived from the coupled mode theory and the Er rate equation [3]. Here, κ represents the coupling efficiency between the resonator and the tapered fiber, and it can be seen that the larger the Er concentration and the higher the coupling efficiency, the higher the oscillation efficiency. By estimating the Er concentration from the oscillation efficiency, the same argument can be made for the case where Er is added to the entire silica film and for the case where Er is coated on the surface of the resonator. In fact, considering the oscillation efficiency of 1% and the under coupling measurement conditions shown in Fig. 2, the Er concentration was found to be about $5 \times 10^{18} \text{ cm}^{-3}$, which is about three times larger than the concentration from the starting solution.

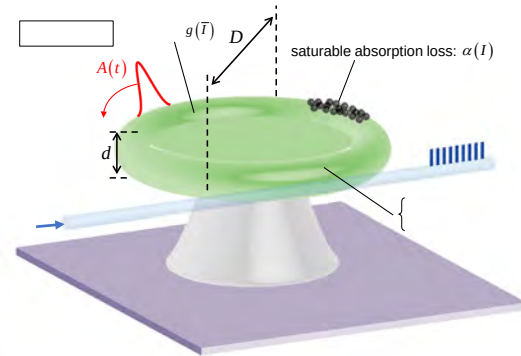


Fig. 1 Schematic illustration of on-chip mode-locked laser with CNT and Er-doped microtoroid.

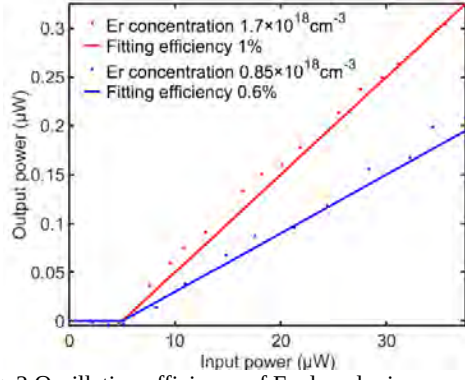


Fig. 2 Oscillation efficiency of Er-doped microresonator.

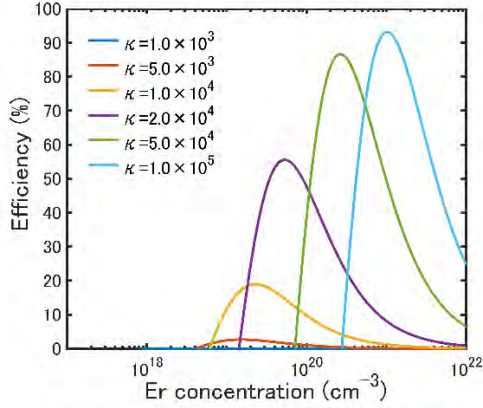


Fig. 3 Relationship between Er concentration per unit volume and oscillation efficiency.

3. The modulation depth of CNT

In our laboratory, apart from the Er-doped microresonators, we measured the saturable absorption properties of toroidal resonators made of silica fabricated by thermal oxidation and coated with a mixture of CNT and PDMS. First, the fabrication method of the CNT/PDMS mixture is shown. First, CNT were added to isopropanol (IPA) and ultrasound was used to break the agglomeration of CNT. The CNT are then diluted with more IPA to achieve the desired CNT concentration. Finally, silicon oil and PDMS were added to the mixture of IPA and CNT, and the IPA was volatilized by heating on a hot plate to produce a mixture of CNT and PDMS.

The mixture of CNT and PDMS was then coated on the toroidal resonator. The coating was performed by attaching the mixture of CNT and PDMS to the tapered fiber and then bringing the toroid resonator close to it. The coating was left at room temperature for 48 hours to cure the PDMS. The thickness of the film by this coating method is about 100 nm, which is inferred from the change in Q factor.

Finally, the modulation depth of the CNT was measured. In the experiment, the CNT coated toroidal resonator was scanned with a pump light at a slow speed of 0.03 Hz. At the same time, the probe light was scanned at a speed of 2 Hz, which was faster than the pump light, and the change in

Q factor was measured. By converting the change in Q factor into a change in absorption coefficient, we obtained a saturation intensity of 15 MW cm^{-2} and a modulation depth of 3.2×10^{-3} .

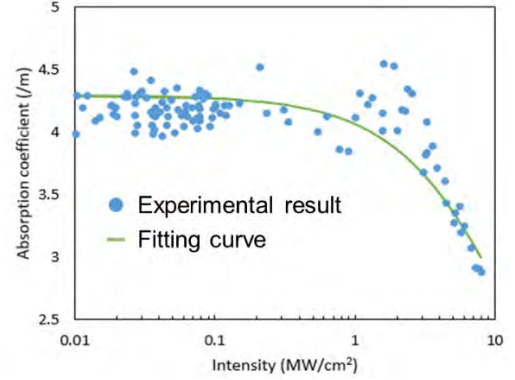


Fig. 4 Measurement results of saturable absorption properties of CNT.

4. Numerical analysis of mode-locking conditions

Since the gain of the Er-doped microresonator and the modulation depth of the CNT were found experimentally, a numerical analysis model in a microresonator was constructed based on these values to clarify the necessary conditions for mode-locking [4].

$$\frac{\partial}{\partial T} A(t, T) = \left(-D \frac{\partial^2}{\partial t^2} + i\gamma |A|^2 \right) A(t, T) + (g - (l + \alpha(t, T))) A(t, T) \quad (1)$$

From the first item on the right, the group velocity dispersion of the resonator, the Kerr effect, which is a nonlinear optical effect, the gain added to the resonator, the loss inherent in the resonator, and the absorption due to saturable absorption are represented. Equation (1) was analyzed using the split-step Fourier method, and the result is shown in Fig. 4. This analysis was performed when the diameter of the resonator was 300 μm and the Q factor was 1×10^7 . The color map shows the Er gain per cavity on the vertical axis, the modulation depth of the CNT on the horizontal axis, and the color bar shows the ratio of the average power inside the cavity to the peak power of the pulse. The experimentally measured Er concentration of $5 \times 10^{18} \text{ cm}^{-3}$ corresponds to a gain of 1×10^{-3} per cavity, which is located at the red line in the color map.

Based on the results of the numerical analysis, it was found that it is difficult to achieve mode-locking with the current gain, but it is possible to achieve mode-locking by improving the gain by a factor of three and optimizing the modulation depth of the CNT. In addition, numerical analysis shows that the gain required for mode-locking decreases when the Q factor of the resonator is improved. In conclusion, we found that 1) improvement of the Q factor of the resonator, 2) improvement of the Er gain, and

3) optimization of the modulation depth of the CNT are necessary for the development of mode-locked lasers.

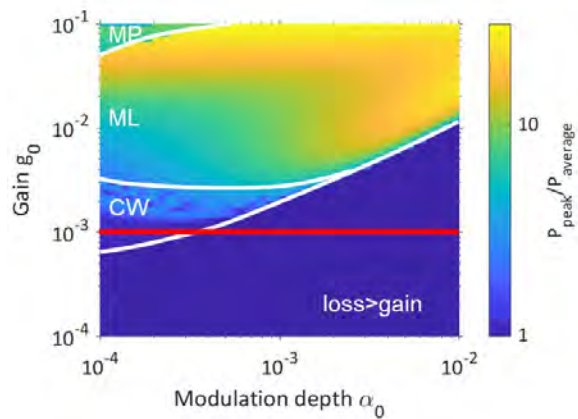


Fig. 5 Analysis results for mode-locked condition.

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Multi-soliton generation in a microresonator with a saturable absorber

Ayata Nakashima (B4)

Dissipative Kerr solitons are generated through a chaotic process. The number of generated solitons is random, and in some cases, no solitons are formed. In order to solve this problem, this study propose to add a saturable absorber to promote the soliton generation. Our numerical analysis shows that this effect leads to a multi-soliton state.

Key words: Dissipative Kerr soliton, Saturable absorber, Multi-soliton

1. Background

Dissipative Kerr solitons are generated when the phases of the longitudinal modes of the optical Kerr comb are locked. They are stable pulses due to the balance of not only a gain and a loss, but also a dispersion and a nonlinearity. It has a wide range of application, including communications, LiDAR, spectroscopy, and atomic clocks. The generation of the solitons are realized by sweeping the wavelength of the pump light entering the microresonator [1]. In this case, however, the solitons are generated through a chaotic state in which the intracavity power fluctuates greatly. Therefore, the number of generated solitons is not always the same. Since the randomness of the number of solitons is undesirable for applications, research to control it, e.g., by using a saturable absorber, has attracted much attention [2].

We focused on the saturable absorber attached to the resonator and studied the effect of it. One of the problems with soliton generation is that due to the random characteristic of the number of the solitons, no solitons are generated even when solitons are needed. However, since the saturable absorber shows weak absorption against strong light and strong absorption against weak light, the pulse generation is promoted by repeatedly receiving the saturable absorption effect in the cavity, and it helps the soliton generation without fail. In this study, we performed simulations with and without a saturable absorber in the resonator to clarify the effect of the saturable absorption property.

2. Simulation model

We consider a silica toroidal resonator with a diameter of 600 μm (FSR of 110 GHz), a dispersion of $-17.7 \text{ ps}^2/\text{km}$, and Q factor of 10^8 . And we assumed that inputting a continuous wave whose power is 100 mW.

The simulation model is given by the Lugiato-Lefever equation, which is a nonlinear Schrödinger equation with the addition of a detuning term and an external input term.

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

The right-hand side represents the loss of the resonator, loss of the saturable absorber, detuning, dispersion,

nonlinear optical effects, and external input, respectively. Equation (1) was calculated using the split-step Fourier method.

The loss caused by the saturable absorber changes nonlinearly depending on the intensity of the light, and the loss is expressed as,

$$q = \frac{\alpha_{\text{SA}}}{1 + \frac{|E(t, \tau)|^2}{P_{\text{sat}}}}. \quad (2)$$

In the calculation with a saturable absorber, Eq. (2) is used, where the modulation depth α_{SA} and the saturation power P_{sat} are assumed to be 4×10^{-3} and 4.46 W, respectively. On the other hand, in the calculation without a saturable absorber, we set $q=0$.

3. Result

Examples of simulation with and without the saturable absorber are shown in Fig. 1 and 2. The detuning δ_0 , the difference between the resonance frequency and the pump light frequency, is normalized as shown in Eq. (3).

$$\delta = 2\delta_0/\alpha_{\text{tot}} \quad (3)$$

From Fig. 1 and 2, it can be seen that the external input created new frequency components, and pulses were generated from a certain point. After that, the power of the pulses increased, and the spectrum widened until the soliton disappeared.

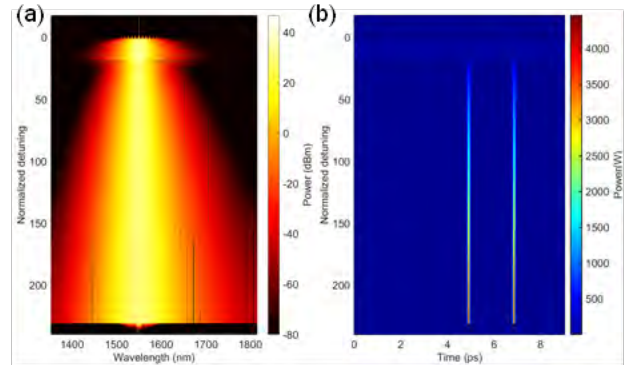


Fig.1: Results when the saturable absorber was added. (a) Wavelength spectrum. (b) Time waveform.

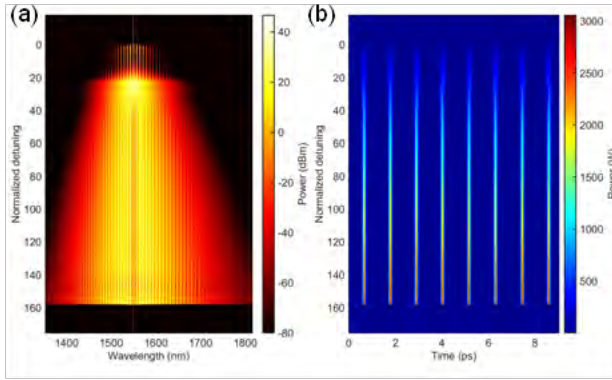


Fig. 2: Results when the saturable absorber was not added. (a) Wavelength spectrum. (b) Time waveform.

By passing through the chaotic region, the process leading to the formation of the solitons and the final number of solitons become random, and thus different results can be obtained even when the same parameters are used. The number of solitons in Fig. 1 and 2 are 2 and 8 respectively, but we cannot obtain these number of solitons every time. Therefore, we repeated the same simulation to investigate the feature of the solitons.

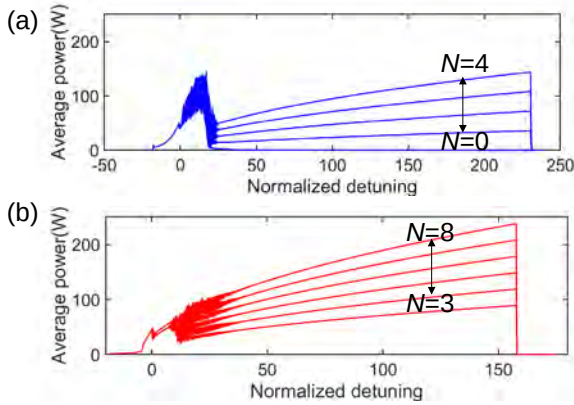


Fig. 3: The transition of intracavity power. (a) Without a saturable absorber. (b) With a saturable absorber.

In Fig. 3, the intracavity power is overplotted. The simulations were performed 100 times. As the wavelength of the pump light was swept, the intracavity power gradually increased. In this region, four-wave mixing starts and a periodic waveform called the Turing pattern is generated. However, the internal power fluctuated in the chaotic region. But when the wavelength of the pump light overtook the resonance wavelength, solitons were formed, and internal power of the resonator became stable.

Figure 3(a) is the case without the saturable absorber and is the result of solving the normal Lugiato-Lefever equation, which is commonly used in the Kerr comb simulation, while the saturable absorption effect is considered in the calculation of Fig.3(b). The difference can be seen in the smaller change in the intracavity power in the chaotic region and the smaller decrease in the intracavity power before the soliton state in Fig.3(b) than in Fig.3(a).

Solitons are formed where the internal power is increasing linearly. Since the power per soliton is almost constant, the intracavity power is proportional to the

number of solitons. Therefore, the number of solitons can be estimated from Fig. 3. The number of solitons in Fig. 3 is from 0 to 4, while in Fig.3 (b), 3 to 8 solitons are formed. The more detailed distribution of the number of solitons is summarized in Fig.4.

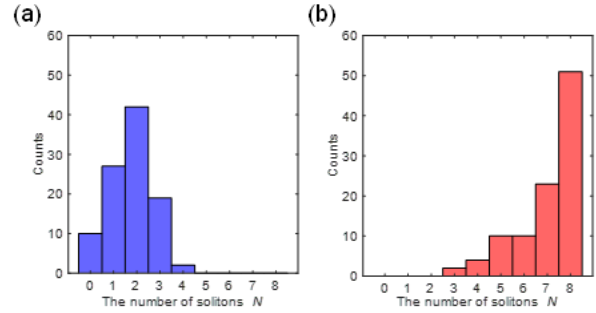


Fig. 4: The number of solitons. (a) Without a saturable absorber. (b) With a saturable absorber.

Figure 4 indicates that the number of solitons is higher on average when the saturable absorber is added. Figure 4(a) shows that there are cases where the number of solitons is 0, while Fig. 4(b) shows that 3 solitons are formed even when the number of solitons is the lowest, which means that solitons are formed without fail every time. Fig.4(b) shows that the number of solitons is 8 in more than half of the 100 simulations. The advantage of adding the saturable absorber is not only the reliable formation of solitons but also the high comb power and high conversion efficiency.

4. Conclusion

In this study, the generation of dissipative Kerr solitons in a microresonator with a saturable absorber was investigated. The simulation model was built by combining the saturable absorption effect into the Lugiato-Lefever equation. As a result, it was found that the number of solitons increases thanks to the saturable absorption effect. This multi-soliton state is expected to be applied to high power and high efficiency combs, as well as to high repetition lasers by controlling the position of the soliton.

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Integrated spatiotemporal multiplexed heralded single photon sources

Koki Yube (M1)

The heralded single photon sources (HSPSs) have a trade-off between the heralded fidelity and the generation probability of the single photon. It is known that the trade-off can be overcome by using time multiplexing. However, the adjustable delay line required for time multiplexing has not been realized in the photonic integrated circuit. In this study, we investigated the performance of the time multiplexed HSPS with the adjustable delay line of photons using optical micro 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.

In this study, we propose time multiplexing of an integrated HSPS using a low-loss adjustable delay line that utilizes the dynamic Q modulation [2] of the coupled resonator of optical micro resonators.

2. Adjustable delay line by using a coupled resonator

In this study, we used Coupled Mode Theory (CMT) to model the coupling system of two optical ring resonators that function as adjustable delay line. Figure. 1 is a schematic illustration of the coupling system. The model equations for this system are given below using CMT.

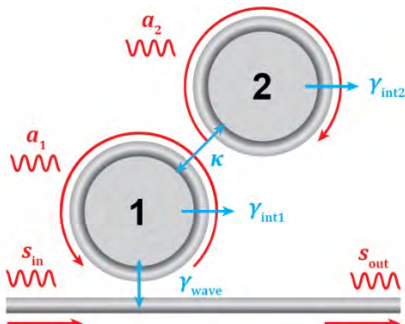


Fig. 1 : Schematic and parameters of CMT model of the coupling system of the optical ring resonators.

$$\frac{da_1}{dt} = \left(j\omega_{a_1} - \frac{\gamma_{int1} + \gamma_{wave}}{2} \right) a_1 + j\frac{\kappa}{2} a_2 + \sqrt{\gamma_{wave}} s_{in} \quad (1)$$

$$\frac{da_2}{dt} = \left(j\omega_{a_2} - \frac{\gamma_{int2}}{2} \right) a_2 + j\frac{\kappa}{2} a_1 \quad (2)$$

$$s_{out} = s_{in} - \sqrt{\gamma_{wave}} a_1 \quad (3)$$

a_1 (a_2); mode amplitude in the gate (storage) resonator. ω_1 (ω_2); resonance angular frequency. γ_{int1} (γ_{int2}); intrinsic loss. s_{in} (s_{out}); mode amplitude in the input (output). γ_{wave} ; coupling loss between the gate and the waveguide. κ ; coupling strength between gate and storage resonator.

Figure. 2(a)-(d) show the optical power and energy obtained from the above equations (1)-(3). A photon is input with the resonance wavelengths of the gate and storage resonator matched (I). When the photon passes through the gate and enters the storage, the resonance wavelength of the gate is shifted to confine the photon in the storage (II). The shift of the resonance wavelength is controlled by the optical Kerr effect. The resonance wavelengths are matched again at an arbitrary time, and the photon stored in the storage are emitted (III). According to the results, the efficiency is 64% which enables an adjustable delay with lower loss than an integrated optical switch (31%). However, the problem is input leakage loss due to the resonator bandwidth.

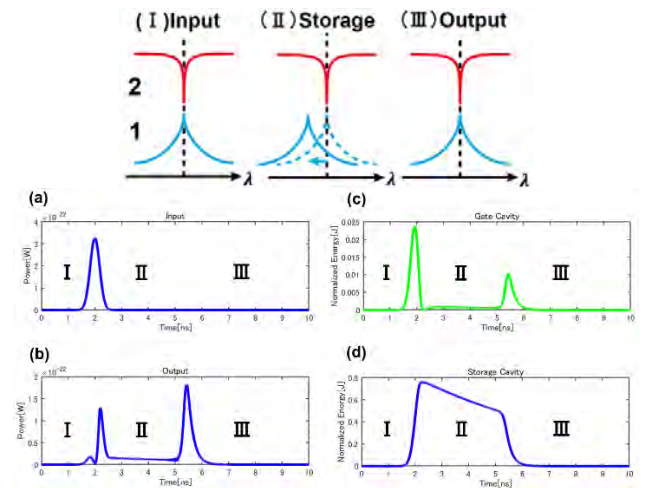


Fig. 2 : (Top) Resonance wavelengths of the gate and storage cavity. (Bottom) Adjustable delay simulation of the coupled resonator system. (a)(b); Input and output optical power. (c)(d); Light energy in the gate and storage resonator.

3. Spatiotemporal multiplexed HSPS

Figure 3 shows the probability calculation model of the spatiotemporal multiplexed HSPS. First, k quantum entangled photon pairs are generated by SPDC with probability $G(k)$. Next, if only one of the k photons is detected (the probability is $D(1|k)$), it is used as a single photon. k photons experience a delay line transmission probability $T(M|j, k)$, of which M photons are emitted.

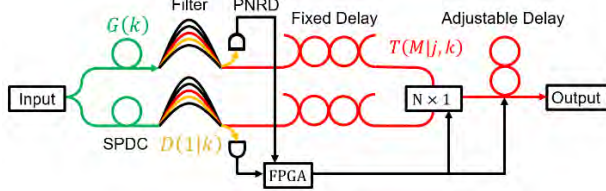


Fig. 2 : Probability calculation model of the spatiotemporal multiplexed HSPS.

$$G(k) = \frac{\mu^k}{(1 + \mu)^{k+1}} \quad (4)$$

$$D(1|k) = \sum_{l=1}^k \eta_t^l (1 - \eta_t)^{k-l} \binom{k}{l} \left(\frac{1}{d}\right)^{l-1} \quad (5)$$

$$T(M|j, k) = (t_i t_{DL}^{N-j+1}) (1 - t_i t_{DL}^{N-j+1})^{k-M} \binom{k}{M} \quad (6)$$

μ ; the mean photon number, k ; the number of generated photon pairs, d ; the photon number resolution, η_t ; the detection efficiency, t_i ; the fixed delay loss, t_{DL} ; the adjustable delay loss, j ; the time bin number, M ; the output number of photons.

Time multiplexing is a method of selectively extracting and emitting a pulse in which a photon pair is generated out of N periodic optical pulses. When a photon pair is generated in the j th time bin, an adjustable delay line that emits photons after delaying $N - j + 1$ times is required. Spatial multiplexing is a method of switching to one of S parallel HSPS in which photon pairs are generated. Figure 4 shows the photon heralding probability (P_H) and single photon emission probability ($P_{M=1}$) due to spatiotemporal multiplexing obtained using the above equations (4)-(6).

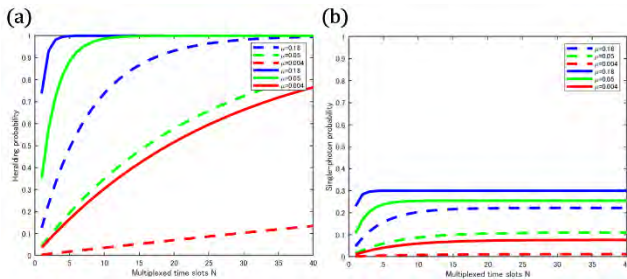


Fig. 4 : Dashed line; Time multiplexing ($N=1\sim 40$). Solid line; Spatiotemporal multiplexing ($S=10$). Blue; ($\mu = 0.18$), Green; ($\mu = 0.05$), Red; ($\mu = 0.004$). (a) Photon heralding probability (b) Single photon emission probability.

As the time multiplicity increases, the heralding probability approaches 1, but the single photon emission probability has an upper limit due to the loss of the delay lines. This is mainly due to the loss of the fixed delay line, which gains time to detect one of the generated photon pairs and control the other based on the detection signal. The integrated fixed delay line has the lowest loss of 0.037 dB/m [3], which is about 2600 times the loss of optical fibers.

4. Coupling Condition

HSPSs need not only to increase the emission probability of a single photon, but also to suppress the emission probability of the multiple photons at the same time. The heralded fidelity F_h and normalized quadratic correlation function $g^2(0)$ are used as indicators for quality evaluation of single photons.

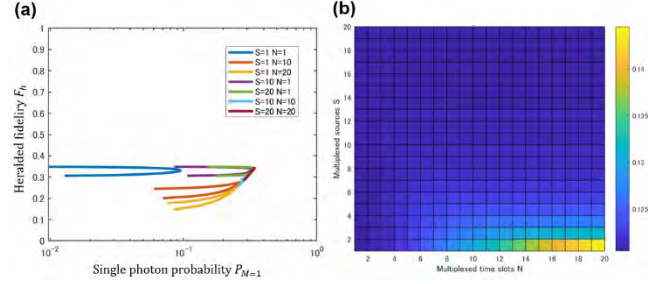


Fig. 5 : a(b); Changes in fidelity and single photon emission probability (normalized quadratic correlation function $g^2(0)$) due to changes in spatiotemporal multiplicity.

$$F_h = \frac{P_{M=1}}{P_H} \quad (7)$$

$$g^{(2)} = \frac{\langle \hat{n}^2 \rangle - \langle \hat{n} \rangle^2}{\langle \hat{n} \rangle^2} = \frac{\sum_{M=0}^{\infty} P_M M(M-1)}{\sum_{M=0}^{\infty} P_M M} \quad (8)$$

Figure 5(a) shows that spatial multiplexing can increase the probability of single photon emission without reducing the heralded fidelity, whereas time multiplexing reduces it. Figure 5(b) shows that multiphoton emission can be suppressed because $g^2(0)$ is low. Considering the two indices together, both the heralded fidelity and $g^2(0)$ are low, indicating that the emitted photon states have a high proportion of single photon states $|1\rangle$ and vacuum states $|0\rangle$. Since the loss of the fixed delay line is large, the probability of generating vacuum states is high. Since this low heralded fidelity can be achieved even with faint coherent laser that is a classical light source, it is desirable to reduce the loss of the fixed delay line.

5. Conclusion

It was demonstrated by simulation that it can be used as a low-loss integrated adjustable delay line by dynamically modulating the coupling Q of the coupled resonator system. We constructed a probability calculation model for a HSPS with spatiotemporal multiplexing and evaluated its performance by using the values obtained by the simulation of the adjustable delay line.

As a future outlook, we aim to experimentally demonstrate the adjustable delay line operation in a single photon state. This adjustable delay line can be applied as a quantum memory in a non-classical states, and is considered to be an important element in quantum information technology using photons.

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Research on hydrogen gas sensor using micro-optical resonator

Ryosuke Mamiya (B4)

Hydrogen gas is one of the most promising cleaning energy sources and the demand for hydrogen sensors is increasing. In this research, to develop a thermal conductivity hydrogen sensor based on a micro-optical resonator, thermal analysis of five models was performed to compare their performance. Calculations show that the silicon 1DPhC resonator is the most sensitive and can detect concentration changes of at least 8.23% at high concentrations (~100%) and up to 2.36% at low concentrations (0%~).

Key words : Micro-optical resonator, hydrogen gas sensor

1. Background

Hydrogen gas is one of the most promising sources of cleaning energy because it is highly efficient in combustion and does not pollute the environment. Hydrogen is colorless, odorless, and dangerous for practical applications because of its explosive potential when its concentration exceeds 4% of the atmosphere. Therefore, there is an urgent need to realize a highly sensitive hydrogen sensor.

So far, various hydrogen gas sensors [1] and sensors using micro-optical resonators [2] have been researched. Although temperature sensors using micro-optical resonators [3] have been put to practical use, gas sensors using micro-optical resonators have not yet been put to practical use.

In this research, we aim to develop a hydrogen gas sensor using a micro-optical resonator based on the principle of a temperature sensor. For this purpose, five micro-optical resonators (silica toroid resonator, silicon 1DPhC resonator, silicon 2DPhC resonator, silica 1DPhC resonator, and polystyrene microsphere resonator) were modeled, and the most suitable one for hydrogen gas sensor was shown by thermal analysis. The sensitivity of the most suitable sensor was also estimated.

2. Principle

In this research, the high thermal conductivity of hydrogen gas relative to air is used for sensing. When an optical resonator resonates, the heat generated by light absorption causes the temperature of the resonator to rise. At this time, the resonance wavelength shifts. If the hydrogen gas concentration is high, the heat is dissipated from the resonator to the surrounding gas, and the temperature rise of the resonator and the resonance wavelength shift become small. The hydrogen concentration is sensed by the size of this resonance wavelength shift.

The heat generated by the optical absorption of silica is expressed by the following equation.

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

η is the coupling efficiency, α_{abs} is the absorption coefficient, λ is the resonance wavelength, and P_{in} is the incident power. The heat generation in silicon is caused by two-photon absorption and is expressed by the following equation.

$$E_g \frac{N}{\tau_c} = \left(-\frac{\pi}{Q\lambda} \sqrt{\frac{nV_{eff}}{\beta}} + \sqrt{\frac{\pi^2 nV_{eff}}{Q^2 \lambda^2 \beta} + P_{in}} \right)^2 \quad (2)$$

V_{eff} is the volume of the resonator and β is the two-photon absorption coefficient.

After calculating the amount of heat generated, the temperature change of the resonator was simulated using COMSOL.

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

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

$\frac{dn}{dT}$ is the TO coefficient.

Since the sensitivity is determined by how much the resonant wavelength shifts with respect to the line width of the resonant wavelength, the sensor sensitivity was roughly calculated by dividing equation (3) by the line width $\delta\lambda$.

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

3. Simulation

Thermal analysis of the optical resonator was simulated using COMSOL Multiphysics. First, micro optical cavity models were created for each material (Figure 1). Next, we set up a mixture of air and hydrogen around these models at 300 K, and observed the temperature change when the hydrogen concentration was changed from 0 to 100% and a constant heat was applied (Figure 2).

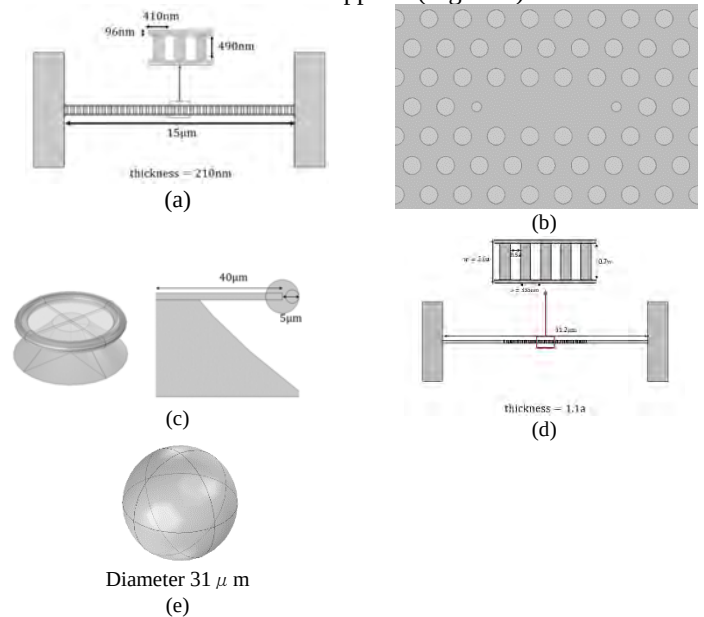


Fig. 1 Models of (a) silicon 1DPhC resonator, (b) silicon 2DPhC resonator, (c) silica toroid resonator, (d) silica 1DPhC resonator, and (e) polystyrene microsphere resonator.

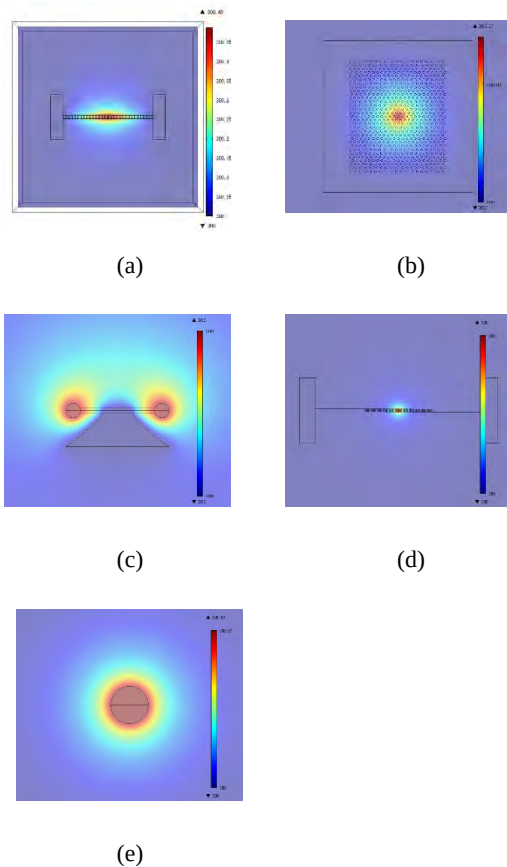


Figure 2 . Temperature distribution of the model when heat is applied (100% air) (a) silicon 1DPhC resonator, (b) silicon 2DPhC resonator, (c) silica toroid resonator, (d) silica 1DPhC resonator, (e) polystyrene microsphere resonator

4. Results

Figure 3(a) shows the resonance wavelength shifts of each model normalized by the linewidth against the hydrogen concentration obtained from the simulation. As can be seen from the graph, the 1D silicon PhC resonator has more than 10 times larger sensor sensitivity than the other models. This is thought to be due to the small resonator volume, large heat generation of silicon, and large TO coefficient.

Next, to approximate the sensitivity of the 1D silicon PhC resonator that had the highest sensor sensitivity, the resonance wavelength shift normalized by the linewidth against hydrogen concentration is shown in Figure 3(b). The graph shows that the slope is largest at low concentrations (high sensitivity), and decreases as the concentration increases (low sensitivity). Assuming that a wavelength shift of half value half width (1/2 of full value half width) is detectable [4], the sensitivity is 8.23% near 100%, and 2.36% near 0% at low concentrations. Considering the explosion limit of hydrogen at low concentrations (4% in air), it is considered difficult to use the sensor at low concentrations. Since the sensor can detect a certain level of hydrogen even at high concentrations, it may be used to monitor and control the hydrogen concentration in a somewhat limited range in hydrogen fuel cells and other hydrogen-based systems.

The sensitivity of the sensor can be improved by

improving the Q-value of the resonator and the detection accuracy of the wavelength shift, and the sensitivity can be further increased by improving the optical resonator production technology.

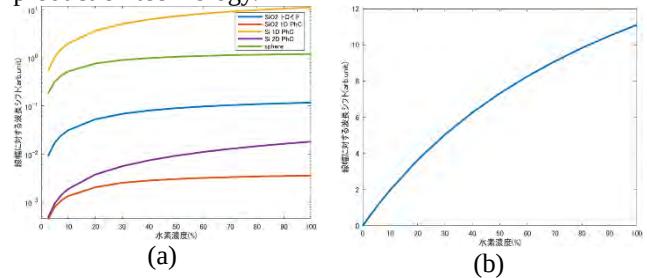


Figure 3: (a) Comparison of linewidth-normalized resonant wavelength shift versus hydrogen concentration (log-log graph) (b) Linewidth-normalized resonant wavelength shift versus hydrogen concentration for 1D silicon PhC resonator.

5. Summary

For the development of a thermal conductivity hydrogen sensor using micro-optical resonators, thermal analyses of five models were performed to compare their performance: silica toroidal resonator, silica 1DPhC resonator, silicon 1DPhC resonator, silicon 2DPhC resonator, and polystyrene microsphere resonator.

Calculations showed that the silicon 1DPhC resonator was the most sensitive, capable of detecting concentration changes of at least 8.23% at high concentrations and up to 2.36% at low concentrations.

The silicon 1DPhC resonator has the advantages of no explosion hazard, operation in the absence of oxygen, and a wide detection range. Therefore, it is considered suitable for use in hydrogen systems with high hydrogen concentration, such as hydrogen fuel cells, rather than for use in explosive concentrations (~4%).

For practical use, the micro-optical resonator is susceptible to various noises due to its high sensitivity, but if we can solve these problems, we believe that we can create a compact, inexpensive, and energy-saving hydrogen sensor.

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Reducing the Cost of Photonic Crystal Spectrometer by Wavelength Conversion Technology

Ryo Sugano (B4) Koki Yube (M1)

Photonic crystal waveguides with chirped structure have different transmittance depending on the wavelength, so they can be used as spectrometers by detecting the emitted localized light. The use of an IR camera to capture light in the communication wavelength band is expensive and is expected to be a problem in industrialization. In this study, I aimed to reduce the cost of the detector by converting the light in the communication wavelength band to visible light using up-conversion.

Key words: Photonic crystal; Spectrometer; Up-conversion;

1. Background

Spectrometer with photonic crystal are superior to conventional spectrometers with diffraction gratings and prisms[1] because they can achieve both small size and high resolution. Among a number of previous studies of spectrometer with photonic crystals[2][3], chirped structure waveguides, in which the waveguide width changes in the waveguide, are very practical because they are resistant to manufacturing errors, which is a problem with nanostructure. For practical use, near-infrared light in the range of 1550 nm, wavelength used for communication, needs to be spectrally detected. However, IR cameras capable of detecting near-infrared light are very expensive.

In this study, I use up-conversion as a wavelength conversion technology, to convert light in the communication wavelength band to visible light, thereby reducing the cost. There are several possible up-conversion devices, but all of them have poor conversion efficiency. To improve the conversion efficiency, we peeled off the upper silica cladding layer that protects the photonic crystal and applied it directly to enhance the interaction between the material and light due to the slow light effect and light localization. Since the chirped waveguide could not detect visible light due to up-conversion, I also observed a one-section waveguide in which the waveguide width did not change.

2. Theory

This study consists of two components: a chirped waveguide of a photonic crystal that serves as a spectroscopic mechanism by emitting localized light from different parts depending on the incident light, and an up-conversion that converts the emitted light into visible light.

First, I explain the spectroscopic structure using the chirped structure. The chirped structure is a

structure in which the waveguide width periodically decreases within the waveguide structure, as shown in Fig. 1(a). Fig. 1(b) shows the relationship between wavelength and output power, and it can be seen that the band gap shifts to the short wavelength side as the waveguide width decreases. The band gap shifts to the short wavelength side as the waveguide width decreases. Since the long wavelength light that cannot be transmitted leak out from the upper and lower layers of the waveguide, the wavelength of the light can be identified by the position of the leakage.

Next, I explain up-conversion. Up-conversion is a technology that converts long-wavelength light with a low energy level into short-wavelength light with a high energy level, and is used to improve the efficiency of photovoltaic power generation and in the field of biological imaging. Up-conversion is different from high-order harmonic generation because the mechanism of generation is different.

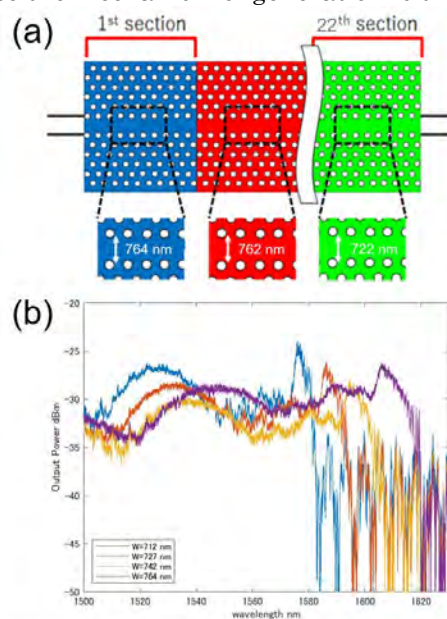


Fig. 1: (a) Diagram of a chirped waveguide. (b) Output power per waveguide width for a single section waveguide with silica cladding layer on top.

3. Coating of the up-conversion element

The use of an expensive IR camera for spectroscopy of near-infrared light is expensive. In this study, I used a method of converting near-infrared light to visible light using Er as a wavelength conversion method by up-conversion. However, as mentioned above, up-conversion has the disadvantage of poor conversion efficiency. As a way to compensate for this disadvantage, the silica cladding layer protecting the silicon layer containing the photonic crystal was removed to form an air bridge structure, and then the silica cladding layer containing Er was prepared by the sol-gel method.

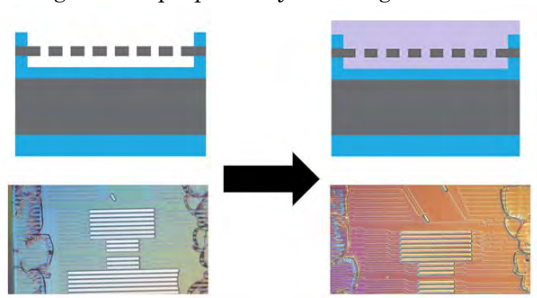


Fig.2: Schematic cross-sectional view (top) and micrograph (bottom) of a photonic crystal chip with an air-bridge structure coated with an up-conversion element by the sol-gel method.

In order to protect the spot size converter that focuses the incident light on the side of the chip when the silica cladding layer is removed, an air-bridge structure was fabricated by spin-coating photoresist, exposing it, and etching it, leaving only the silicon layer with the photonic crystal.

The air-bridged photonic crystal chip was spin-coated with a sol-gel solution containing Er at a speed of 6,000 rpm in an ethanol atmosphere. After that, it was dried at 500°C in a diffusion furnace.

4. Localized light leaking out of the waveguide

The localized light leaking from the photonic crystal waveguide chirped by Er was photographed using an IR camera and a CMOS camera; the CMOS camera was used to capture the upconverted visible light.

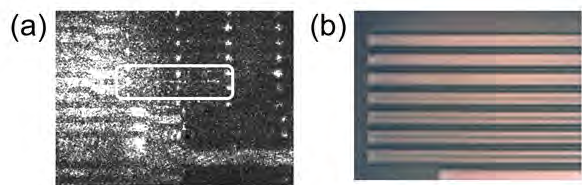


Fig.3: (a) Image of a chirped waveguide taken by an IR camera. (b) Image of the same composition with a CMOS camera amplifying the light.

Fig. 3 (a) shows that light is leaking out in a straight line inside the white frame, indicating that light is properly entering the waveguide. However, (b) shows that no light was observed by the CMOS camera. The background light was turned off, but it could not be observed. In the chirped structure, I could observe the localized

light with the IR camera, but I could not observe the visible light. This is because localized light leaks out from different places in the chirped structure, and the amount of light leaking from one section is small. Therefore, it is thought that the visible light could not be observed.

Therefore, I attempted to capture the up-conversion light again using a waveguide with only one section, which is not a chirped structure. I obtained images using light at a wavelength of 1591.1 nm, which is near the mode gap where the slow light effect is most pronounced. Fig. 4(a) shows the localized light in the near-infrared. However, Fig. 4(b) shows that visible light could not be observed as in the chirped waveguide.

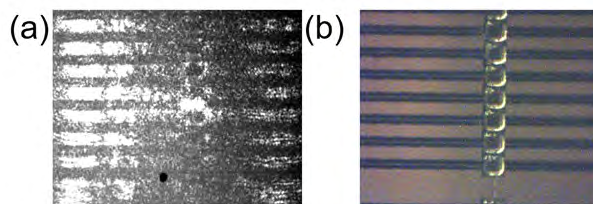


Fig.4: (a)Image obtained using an IR camera with 0 dBm light input. (b)Image obtained using a CMOS camera with 30 dBm light amplified by an amplifier.

5. Verification

Since no visible localized light could be observed, it was necessary to confirm that the silica cladding layer was properly formed. Therefore, I compared the position of the mode gap before and after the silica cladding layer was removed and after the coating as shown in Fig. 5(a). The position of the mode gap after coating is between before and after the silica cladding layer, indicating that the Er-containing silica cladding layer has been properly coated. In order to determine the thickness of the Er-containing silica cladding layer, the model shown in Fig. 5(b) was created by simulation, and the band gap diagram shown in Fig. 5(c) was generated. The thickness of the silica cladding layer was predicted to be between 100 and 300 nm from the simulation results. The thickness of the silica cladding layer was predicted to be 100-300 nm from the simulation results, which is consistent with the empirical values obtained in our laboratory. The thickness of the silica cladding layer is 100-300 nm, which is consistent with the experimental data obtained in our laboratory, suggesting that there is sufficient Er on the photonic crystal waveguide.

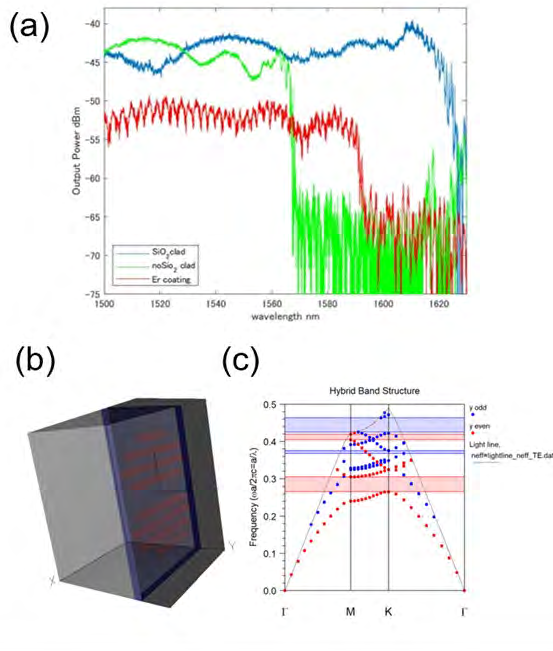


Fig.5: (a) Output power before and after removing the silica cladding layer and after coating. (b) Model of the photonic crystal chip fabricated to calculate the band gap by simulation. Blue is the silicon layer, red is the pores, and black is the silica cladding layer. (c) Band gap diagram of (b).

6. Summary

By creating a silica cladding layer with Er doped after the air bridge structure, I aimed to reduce the cost of light detection by using visible light. Localized light in the communication wavelength band was confirmed, but visible light could not be observed. I verified the thickness of the silica cladding layer and found it to be sufficient. Therefore, it is necessary to reconsider the up-conversion element.

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Statistical Data

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Awards

- [1] Apr-2020 The 9th Advanced Laser and Photon Sources, The Best Student Oral Paper Award, Keigo Nagashima
- [2] Apr-2020 The 9th Advanced Laser and Photon Sources, The Best Student Oral Paper Award, Shota Sota

Dissertations

PhD thesis:

Shun Fujii, Dispersion engineering of high-Q optical microresonators for frequency comb generation

Master thesis:

Jocelyn Jacques Hofs L., “Light Frequency Detection in a Chirped Photonic Crystal Waveguide Spectrometer Using Deep Learning” (2020 September)

Riku Imamura, “Fabrication of High-Gain Er-Doped Microresonators and Their Optical Properties”

Tamiki Otsuka, “Efforts Toward Microcomb Generation and Transmission Applications Using Silicon Nitride Microresonators”

Koichiro Handa, “Research on the Fabrication of Low-Loss Microresonators Using Silicon Nitride Deposition Under Low-Temperature Conditions”

Bachelor thesis:

Ryosuke Mamiya, “Research on Hydrogen Gas Sensing Using Micro Optical Resonators”

Shuto Sugawara, “Study on Transmission Using Raman Combs”

Ryo Sugano, “Research on Communication Wavelengths Using Visible-Light Detectors”

Ayata Nakashima, “Research on Soliton Pulse Formation in Micro Optical Resonators with Saturable Absorption”

Soma Kogure, “Generation and Control of Soliton Combs in SiN Ring Resonator”