様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

# 科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Development of rare-earth oxide based optical amplifiers and lasers integrated on Si by using magnetic light-matter interactions

研究課題名（英文）Development of rare-earth oxide based optical amplifiers and lasers integrated on Si by using magnetic light-matter interactions

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研究成果の概要（和文）：MBE法でSOI基板上に高品質な単結晶酸化希土類薄膜を成長できた。光増幅器を実現するため、低損失(2.3 dB/cm)かつ閉じ込め係数の大きい(~42%)導波路構造を実証された。光ポンプによる導波路中24 dB/cmの信号増幅を測定でき、Erイオンが吸収から透明まで反転できたことが分かった。レーザーを実現するため、高Q値マイクロリング共振器を実証された。また、Erイオンの電気と磁気ダイポール遷移の光特性を調べるため、高Q値metasurface構造も設計した。更に、低温光学測定よる、該当導波路及び共振器構造は、集積化量子光デバイスにも有望なプラットフォームとなることが分かった。

研究成果の学術的意義や社会的意義
シリコン上にモノリシック集積可能な光増幅器とレーザーはシリコンフォトニクスにおいて最も重要かつ実現されてない要素デバイスである。本研究で実証された酸化希土類薄膜材料及びデバイス構造では、これらのデバイスの実現に非常に有望なプラットフォームと言え、モノリシック光集積回路技術に活用できると期待される。

研究成果の概要（英文）：High quality single-crystal rare-earth oxide thin films (Gd2O3 and (ErGd)2O3) have been successfully grown on silicon-on-insulator substrate by using molecular beam epitaxy method. For realization optical amplifiers, a waveguide platform with low loss (2.3 dB/cm) and large optical confinement factor (~42%) has been demonstrated. Through pump-probe measurement, optical signal enhancement up to 24 dB/cm has been obtained in the waveguide and material transparency has been achieved. Microring resonators with high Q-factors have also been demonstrated for realizing lasers. High Q-factor metasurface structures have also been designed for investigation and manipulation of light emission of electric dipole and magnetic dipole transitions of Er3+ ions. Finally, the demonstrated waveguides and resonators have also found to be a promising platform for integrated quantum optical devices.

研究分野：応用物理工学

キーワード：希土類イオン　光増幅器　レーザー　シリコンフォトニクス　光導波路　ナノ共振器

## １．研究開始当初の背景

Silicon photonics has become an attractive platform for several emerging applications, including light detection and ranging for autonomous driving, optical frequency combs for parallel communication and optical sensing optical neural networks for artificial intelligence, quantum information processing, etc. The maturation of these exciting areas relies significantly on ultra-large scale and low cost monolithic-integration of variety of silicon photonic components, in which laser sources still remain a major challenge.

An ideal laser for such purpose should satisfy several requirements, including (1) emission wavelength in telecom band and wide tunable ability, (2) electric driving capability, (3) small device footprint, and most importantly (4) fabrication compatible with mature complementary metal-oxide semiconductor (CMOS) process. So far, several types of Si-based lasers have been demonstrated, including Si Raman lasers, III-V lasers on Si by bonding or epitaxial growth, and Ge/GeSn lasers on Si by epitaxial growth. However, neither of them could fulfil all of these requirements simultaneously. For example, Raman lasers couldn't be electrically pumped and the gain bandwidth is too small; the compatibility of III-V lasers to CMOS process is still controversial; the lasing wavelengths of Ge/GeSn are shifted away from telecom band.

Compared with aforementioned approaches, erbium (Er)-doped lasers have potential to be a promising solution due to the fact that emission wavelength of $Er^{3+}$ ions is around 1.55 µm, the gain bandwidth is relatively wide, and $Er^{3+}$ ions can be doped into variety of host materials compatible with CMOS process. The main obstacle towards efficient, low threshold, and miniaturized lasers is rather low optical gain due to low Er concentration. High Er concentration is thought to be difficult to achieve in most host materials. Therefore, novel materials and device structures are thus highly desirable to solve these problems.

## ２．研究の目的

This research aimed to demonstrate silicon-based monolithic-integrated optical amplifiers and lasers by using single-crystal Er-doped rare-earth oxide (REO) thin films epitaxially grown on silicon substrate as gain medium, and high refractive index subwavelength dielectric resonators with strong magnetic response as optical structure.

## ３．研究の方法

The research has been conducted through the following steps: (1) Investigation of optimized molecular beam epitaxy (MBE) growth conditions for high quality Er-doped REO thin films on Si substrate; (2) Design and fabrication of novel waveguide structures with low propagation losses and large optical confinement factors for realization of optical amplifiers; (3) Characterization of optical gain in the fabricated waveguides; (4) Design and fabrication of novel optical resonator structures with high Q-factors for realization of lasers.

## ４．研究成果

(1) Growth of high quality REO thin films on Si by MBE

$Gd_2O_3$ was chosen as the REO host material since it is one of the most lattice-matched REOs with Si. Er-doped $Gd_2O_3$ thin films were grown on silicon-on-insulator (SOI) substrate by using high purity Gd and Er metal sources and $O_2$ gas molecular or plasma. Preparation of a clean and flat surface for SOI substrate is critical for the proceeding thin film growth and we found that this could be achieved by a combination of ex-situ wet chemical cleaning and in-situ thermal cleaning, followed by growth of a thin layer of Si buffer. For REO epitaxy, the ratio between the flux rate of rare-earth metals (Gd, Er) and $O_2$ gas flow rate should be carefully tuned in order to achieve stoichiometric conditions. Furthermore, the substrate temperature during growth should be also optimized to obtain sharp interfaces between $Gd_2O_3$ and Si. With the optimized growth conditions, we were able to grow high quality single-crystal $Gd_2O_3$ and $(Er_xGd_{1-x})_2O_3$ thin films with atomically smooth surface, sharp interfaces without interfacial amorphous layers and film thickness up to ~ 200 nm. For $(Er_xGd_{1-x})_2O_3$, Er composition x can be controlled down to ~3%. Intense photoluminescence (PL) with narrow emission peaks can be observed at room-temperature in the telecommunication band for all compositions fabricated. PL decay lifetime as long as 5.4 ms has been obtained for $(Er_xGd_{1-x})_2O_3$ film with Er composition of x = ~3.26%.

(2) Demonstration of waveguide structure for optical amplifiers

A low-loss waveguide platform has been proposed and demonstrated, in which a cap layer of silicon nitride (SiN) is deposited on top of REO thin film and patterned into a strip-loaded configuration (Fig. 1(a)). The TM mode of the waveguide, which is the polarization used in the device, is found to have large leakage loss. However, by properly choosing the waveguide width, the leakage loss could be eliminated (Fig. 1(b)), where a bound state in the continuum (BIC) is formed. This peculiar behavior could be confirmed from the mode profiles of the waveguides with different widths (Fig. 1(c) and 1(d)). Furthermore, large optical confinement factors in REO thin films can be obtained. With a rather thin REO layer (< 100 nm), an optical confinement factor of ~18% can be readily achieved (Fig. 1(b)).

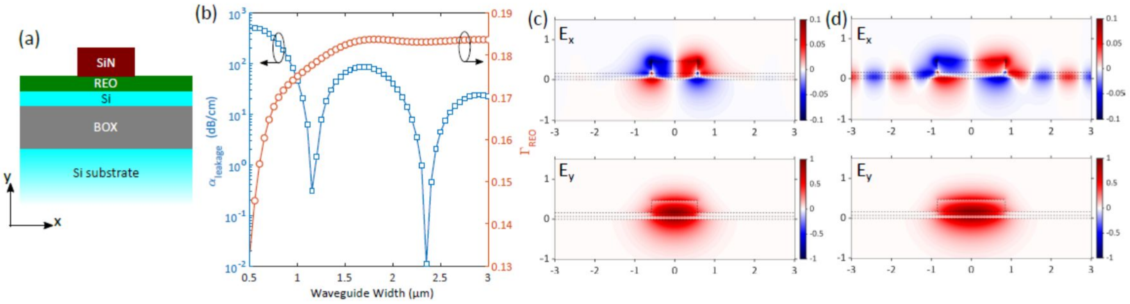


Figure 1. (a) Cross-section schematic diagram of the proposed SiN/REO/SOI strip-loaded waveguide. (b) Calculated leakage loss αleakage and mode confinement factor $\Gamma_{REO}$ of fundamental TM modes of waveguides with different widths. (c) and (d) Mode profiles of the waveguides with widths of 1.15 and 1.70 μm, respectively. Minority Ex and majority Ey components of electric field are plotted, both of which are normalized to corresponding Ey maximum.

The proposed waveguide structure has been realized experimentally by using electron beam lithography and reactive ion etching (Fig. 2(a)). Propagation losses of waveguides with three different widths were characterized, and a minimum loss of 4.7 dB/cm at 1445.8 nm for 1.08-μm-wide waveguide is obtained (Fig. 2(b)). Besides, $Er^{3+}$ ion absorption can be clearly observed as dips in the loss spectra (Fig. 2(b)). A further development through increasing the thickness of $(Er_xGd_{1-x})_2O_3$ has been performed and a lower propagation loss of 2.3 dB/cm and a larger confinement factor of 42% have been achieved, which is the lowest loss demonstrated so far for Si-based REO waveguides.

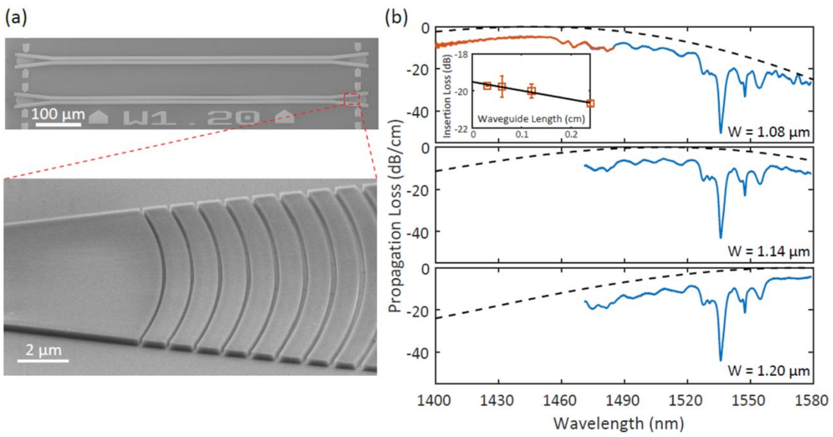


Figure 2. (a) SEM image of a fabricated waveguide, together with magnified view of grating coupler section. (b) Extracted propagation loss spectra of waveguides with width of 1.08, 1.14, and 1.20 μm. Solid curves indicate loss spectra; dashed curves are calculated leakage loss spectra without consideration of $Er^{3+}$ ion absorption. For W = 1.08 μm, solid curves with different colors (blue and orange) were measured by two tunable lasers with different wavelength ranges. The inset shows the insertion loss of waveguides with different lengths at a wavelength of 1445.8 nm.

(3) Demonstration of optical amplification

Optical amplification of the aforementioned waveguides were measured by pump-probe method, in which the transmission of weak probe laser (1510 ~ 1560 nm) through the waveguides was measured with and without pump laser (~1465 nm) input. Optical signal enhancement up to ~24 dB/cm was observed at 1536 nm (Fig. 3), while the total loss of the waveguides without pumping was ~26 dB/cm. Provided that the passive loss at 1536 nm was larger than 2.3 dB/cm, the transparency of the gain medium has been achieved.

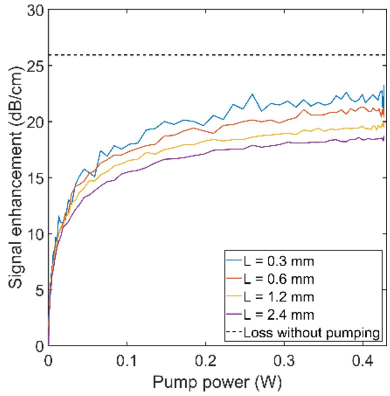


Figure 3. Measured optical signal enhancement upon different pump powers for waveguides with different lengths. The dashed line indicates the total loss of the waveguides without pumping.

The dependence of optical signal enhancement on the Er doping concentration was also investigated (Fig. 4). As the doping concentration decreases, a clear increasing of population inversion ratio (ratio of signal enhancement to absorption) was observed. Therefore, by decreasing the Er concentration further, it is highly expected that the signal enhancement will overcome total loss, thus net optical gain should be realized.

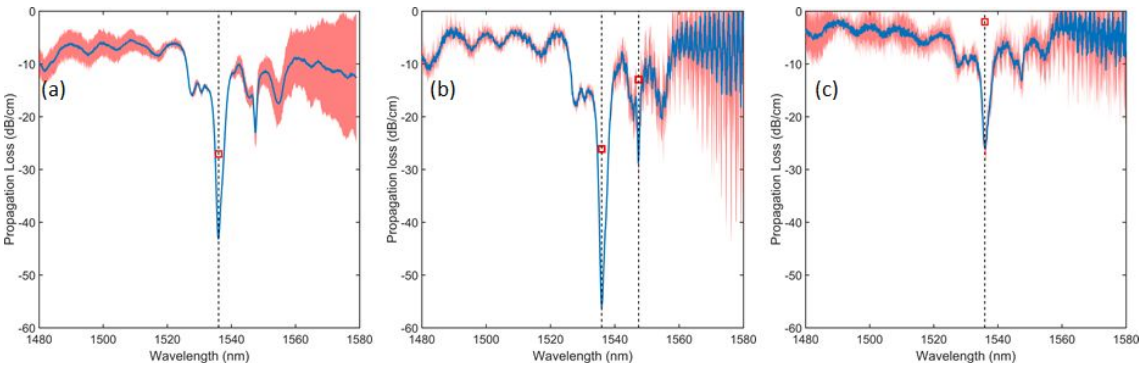


Figure 4. Spectra of propagation loss for waveguides width different Er compositions $x_{Er}$: (a) 9.15%, (b) 6.83%, and (c) 3.26%. Red-patched area indicates error bar for the propagation loss. Red dots in each figure indicate reduce propagation loss due to optical signal enhancement upon pumping.

(4) Design and demonstration of high Q-factor optical resonators for lasers

For realization of lasers, microring resonators based on aforementioned waveguides has been demonstrated (Fig. 5(a)). From the measured transmission spectrum (Fig. 5(b)), high Q-factors (>$10^5$) has been demonstrated. Such high Q-factors indicate that the extra loss induced by microring resonators is very small. Therefore, lasers can be readily achieved once net optical gain is obtained.

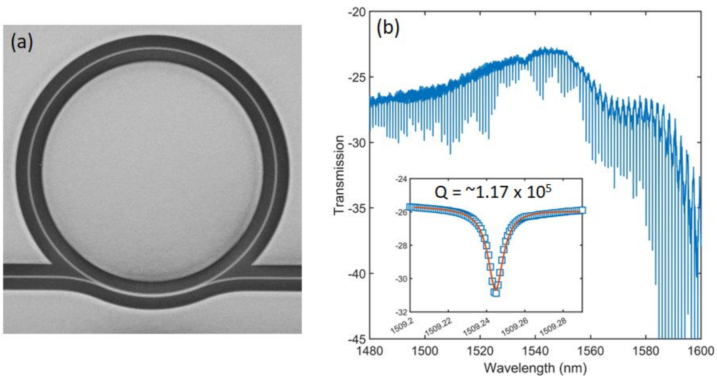


Figure 5. (a) SEM image of a fabricated microring resonator. (b) Transmission spectrum of microring resonator. Inset shows zoomed view of one of the resonances around 1509 nm, together with its Lorentz fitting, showing a Q-factor of $1.17\times10^5$.

To investigate and manipulate light emission of electric dipole (ED) and magnetic dipole (MD) transitions of $Er^{3+}$ ions in REO thin films, metasurface structures with enhanced electric or magnetic field in REO have been designed (Fig. 6(a)). The structures were based on Si/REO/SOI layer stacks, and the unit cell structure is an asymmetric mesa of patterned Si on REO thin film. By adjusting geometric parameters, high-Q resonances in the wavelength range of optical transitions of $Er^{3+}$ ions have be realized, with enhanced electric or magnetic fields localized in REO thin film, respectively (Fig. 6(b) and 6(c)). The designed structure can be used to selectively enhance ED and MD emission of $Er^{3+}$ ions, as well as to serve as optical resonators for realization of lasers.

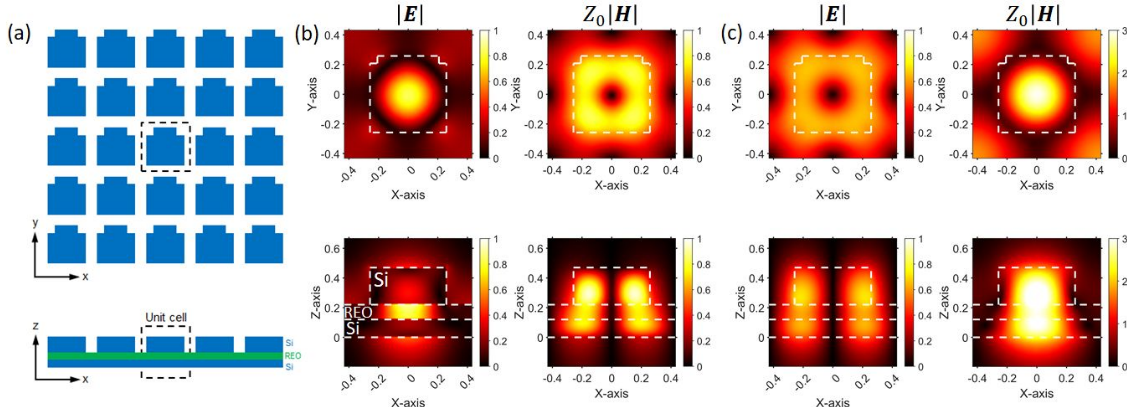


Figure 6. (a) Schematic diagram of the proposed metasurface structure. (b) Resonant mode profile of an ED resonance, with a Q-factor of $4.39\times10^5$. The electric field in the REO layer is much stronger than magnetic field. (c) Resonant mode profile of an MD resonance, with a Q-factor of $6.02\times10^6$. The magnetic field in the REO layer is much stronger than electric field.

(5) Feasibility as a platform for integrated quantum optical devices

The aforementioned waveguides and resonators have also been characterized at cryogenic temperature (~2.3 K). Ultra-narrow optical absorption and emission peaks (~ 100 GHz), as well as long lifetime (~10 ms) were observed, indicating high crystal quality of the $(ErGd)_2O_3$ layer and potentially long coherence time of Er ions. The materials and device structure demonstrated here are therefore also a promising platform for quantum optical devices, such as integrated quantum memories.

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Erbium-doped Rare-Earth Oxide Thin Film Waveguides for Integrated Quantum Photonic Devices

３．学会等名
The 15th Pacific Rim Conference on Lasers and Electro-Optics (CLEO Pacific Rim, CLEO-PR 2022)（国際学会）

４．発表年
2022年

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| １．発表者名<br>Ryuichi Ohta, Takuya Hatomura, Masaya Hiraishi, Victor M. Bastidas, Xuejun Xu, Katsuya Oguri, William J. Munro, Hajime Okamoto |
| ２．発表標題<br>Compression of the Inhomogeneous Broadening of Ensemble Rare-earth Ions Using a Mechanical Resonance |
| ３．学会等名<br>The 15th Pacific Rim Conference on Lasers and Electro-Optics (CLEO Pacific Rim, CLEO-PR 2022)（国際学会） |
| ４．発表年<br>2022年 |

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| １．発表者名<br>Masaya Hiraishi, Tomohiro Inaba, Xuejun Xu, Haruki Sanada, Tai Tsuchizawa, Atsushi Ishizawa, Takehiko Tawara, Jevon Longdell, Katsuya Oguri, Hideki Gotoh |
| ２．発表標題<br>Spectroscopic examination of optical coupling between erbium ions and microring resonators on Si-integrated on-chip devices |
| ３．学会等名<br>The Dodd-Walls Centre Symposium 2022（国際学会） |
| ４．発表年<br>2022年 |

〔図書〕　計0件

〔出願〕　計1件

| 産業財産権の名称 | 発明者 | 権利者 |
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| 光導波路 | 徐学俊、俵毅彦、土澤泰 | 同左 |
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〔取得〕　計0件

〔その他〕

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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

| 共同研究相手国 | 相手方研究機関 |
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