Fabrication of erbium-doped silica toroid microcavity and theoretical consideration for lasing
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We fabricated an erbium-doped silica toroid microcavity using ion implantation and evaluated its characteristics by optical measurement. We also calculated the threshold condition for lasing and developed a re-design proposal as regards quality factor and erbium concentration.

Key word: erbium-doped silica toroid microcavity, Lasing, Coupling mode theory, Rate equation

1. Introduction

An optical microcavity is a device that can confine light and store it in a very small space for a long time. The silica toroid microcavity, which is a whispering gallery mode cavity, has a high quality factor and a small mode volume and is suitable for integration. Rare earth elements have very useful properties for optical devices. In particular, erbium exhibits photoluminescence around 1550 nm, which is the wavelength used in telecommunication. Therefore, erbium is used in fiber amplifiers (EDFA) and fiber lasers.

The combination of a silica toroid microcavity and erbium can create new applications. In fact, erbium-doped silica toroid microcavities are used in sensing [1], add-drop filters [2], and parity-time symmetry [3].

In this research, we aimed at lasing and fabricated an erbium-doped silica toroid microcavity using ion implantation as a first step towards application. Moreover, we considered the lasing threshold condition theoretically using coupling mode theory and a rate equation.

2. Lasing threshold condition

To calculate the lasing threshold condition, we used an equation of motion for the lasing mode and a rate equation for the erbium laser system [4].

\[
\frac{da_s}{dt} = -\frac{1}{2\tau_s}a_s + g_s a_s
\]

\[
\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 - \frac{N_2}{T}
\]

Where \(a_s\) is the internal cavity field at the lasing wavelength, \(\tau_s\) is the cavity photon lifetime, \(g_s\) is the intracavity gain coefficient depending on the mode, \(N_1, N_2\) is the ground state (or excited state) population, \(W_{12}, W_{21}\) is the absorption (or stimulated emission) transition rate, and \(T\) is a spontaneous emission lifetime. \(g_s\) is determined by \(N_1, N_2\). The lasing threshold condition is given by setting the first equation at zero (i.e., when the gain compensates for the total cavity losses).

Figure 1 shows the lasing threshold condition calculated by substituting a typical value for \(W_{12}, W_{21}, T\). For example, \(Q_0 = 1 \times 10^7\) and when the erbium concentration is about \(2.8 \times 10^{18}\) cm\(^{-3}\), lasing can be obtained.

3. Fabrication

First, erbium ions are implanted in a SiO\(_2\)-Si substrate (SiO\(_2\) thickness is 1 \(\mu\)m). The subsequent processes are the same as those used for an undoped silica toroid microcavity. All the samples are implanted with 194 keV at a fluence of \(7 \times 10^{14}\) cm\(^{-2}\). When SiO\(_2\) is wet-etched in HF, the outer perimeters of the microdisks are undercut and the implanted erbium ions disappear. We assume that this undercut is because ion implantation made the SiO\(_2\) structure fragile. To prevent this, we dry-etched the SiO\(_2\) in CHF\(_3\), then the microdisks warped but there was no undercut. These warped microdisks were transformed into well-sharped toroid microcavities by CO\(_2\) laser reflow.

Figure 2: Processes for fabricating erbium-doped silica toroid microcavities. [J. Kalkman, et al., J. Appl. Phys. 99, 1-9 (2006)]
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Fig. 3: (a,b) SEM image of two microdisks fabricated by (a) HF wet etching (b) CHF₃ dry etching. (c) SEM image of erbium-doped silica toroid microcavity.

4. Evaluation of characteristics

An intrinsic $Q$ of $3.58 \times 10^5$ was derived from the measured transmittance spectrum of a fabricated microcavity. From Fig. 1, the erbium concentration required for lasing with this intrinsic $Q$ is $1.0 \times 10^{20}$ cm$^{-3}$. Assuming that the erbium ions were diffused homogeneously by the laser reflow, a fluence of $7 \times 10^{15}$ cm$^{-2}$ corresponds to a concentration of $7 \times 10^{18}$ cm$^{-3}$ and cannot reach the lasing threshold condition. In fact, despite pumping at 1480 nm lasing was not obtained.

To evaluate the microcavity characteristics, we measured the variation in quality factor caused by pumping. When pumped at 1481 nm, the measured quality factors varied slightly from $Q_{\text{tot}} = 1.13 \times 10^5$ to $Q_{\text{tot}} = 1.18 \times 10^5$, and similar results were obtained multiple times. We assume that the slight increase in quality factor is due to the gain of the pumped erbium ions.

To consider this result, we introduce the quality factor dependence on erbium gain.

$$\frac{1}{Q_{\text{Er}}} = \frac{\lambda}{2\pi n} \left[ -\frac{N_g}{N_{\text{Er}}} (\alpha + g\gamma) + \alpha \right]$$ (3)

$$\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_0} + \frac{1}{Q_e} + \frac{1}{Q_{\text{Er}}}$$ (4)

Where, $\lambda$ is the resonance wavelength, and $N_{\text{Er}} = N_g + N_e$. $\alpha, g\gamma$ were defined as $\alpha = N_{\text{Er}}\sigma^g$, $g\gamma = N_{\text{Er}}\sigma^e$. In these expressions $\sigma^g, \sigma^e$ were the absorption/emission cross-sections of erbium ions at the resonance wavelength. From these equations, pumping with the theoretical quality factor $Q_{\text{tot}} = 1.20 \times 10^5$ was calculated, which agreed well with the experimental value.

5. Re-design proposal

In this research, the main reason for no lasing is that the cavity quality factor is too low. By improving the fabrication processes, we will obtain $Q_0 = 1 \times 10^7$, namely the value that an undoped silica toroid microcavity generally obtains. We used substrates with a 1 μm SiO$_2$ thickness but thin silica disks tend to warp and silica toroids are also the same after laser reflow. The heat of the dry etching processes denatures the photoresist and it becomes hard to remove. The remaining photoresist reduces the quality factor. Moreover, because ion implantation damages the silica structure, the implantation process is often followed by thermal annealing but in this research we substituted laser reflow for thermal annealing. On the basis of the above, we considered improvements in the fabrication processes that use substrates with 2 μm SiO$_2$ thickness, careful removal of the photoresist by O$_2$ ashing, and performing thermal annealing after ion implantation.

With regard to the erbium concentration, when $Q_0 = 1 \times 10^7$ is obtained, an erbium concentration of $2.8 \times 10^{18}$ cm$^{-3}$ is required for lasing, and so a fluence of $5.6 \times 10^{14}$ cm$^{-2}$ is required (assuming that erbium ions are diffused homogeneously by laser reflow).

References