Research Article

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Numerical analysis of a single-mode microring resonator on a YAG-on-insulator

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Abstract: A numerical analysis of a compact microring resonator that was defined on a yttrium-aluminum-garnet (YAG) thin film bonded on top of a SiO₂ cladding layer and operated at the wavelengths of approximately 1.064 and 1.6 μm was performed. The single-mode conditions of YAG waveguides at different waveguide geometries and their propagation losses at different SiO₂ cladding layer thicknesses were systematically analyzed. The key design parameters of the microring resonator, such as gap size and ring radius, were simulated based on the 2.5-dimensional variational finite-difference time-domain method. This study could be helpful in understanding the mechanism of microring resonators defined on YAG thin films and fabricating integrated microlaser sources on YAG-on-insulators.

Keywords: microring resonator, 2.5D varFDTD, microlaser, YAG-on-insulator

1 Introduction

Yttrium-aluminum-garnet (Y₃Al₅O₁₂, YAG) is one of the most important materials for solid-state lasers because of its unique optical and physical properties, such as

high mechanical features, good optical uniformity, and excellent thermal conductivity [1–3]. Moreover, Y³⁺ ions in YAG have ionic radii similar to those of most rare-earth ions; thus, they are more favorable for rare-earth doping [4]. At present, neodymium-doped yttrium-aluminum garnet (Nd:YAG) is considered to be the most promising laser material. Due to its excellent optical and thermo-mechanical characteristics, such as high emission cross section, large pump absorption coefficient, high thermal diffusivity, and low thermal expansion coefficient, Nd:YAG is the most widely used gain medium for high-power and high-efficiency laser output [5–9]. Erbium-doped yttrium-aluminum garnet (Er:YAG) is another important laser material because of its rich energy level structure [10,11]. Depending on different Er³⁺ ion concentrations, Er:YAG can emit 1.6 and 2.94 μm laser waves at room temperature. Among them, the 1.6 μm band laser is located in the atmospheric window and the L-band of an optical communication system and pertains to the safe band of human eyes; thus, it contributes to many applications in optical communication, laser ranging, and remote sensing [12–14]. For example, methane gas has a strong absorption peak in the 1.6 μm band; hence, the 1.6 μm band is a very suitable laser source for methane greenhouse gas differential absorption lidar [15].

In recent years, microring lasers have gained great research interest because of their potential role as very compact light sources with a low pump threshold in the field of optical communications [16–18]. Microring lasers are also used as sensors because of their small size and high sensitivity [19,20]. Silicon, silicon nitride, silicon dioxide, diamond, and even polymers are very popular for different platforms to manufacture microring resonators [21–23]. In contrast, YAG microring resonator, which is developed based on good active material YAG, exhibits excellent performance in optical features. It is more suitable to study the preparation of microring laser. Therefore, the coupling of the excellent optical and thermal characteristics of YAG crystals with the compact structure and high sensitivity of microring resonant cavities is a promising approach for the development of integrated microlaser sources. It is difficult to fabricate microring

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structures using traditional YAG waveguides, such as laser direct writing and ion implantation, because of the small refractive index difference between these waveguides and surrounding media [24,25]. YAG-on-insulators (YAGOI) are preferred materials for the fabrication of YAG microring resonators [26]. The high refractive index difference between a cladding layer (SiO_2) and a YAG film results in strong light guidance, which is suitable for the fabrication of high-performance integrated devices with a small footprint, especially microring resonators. However, no studies have yet conducted simulation analyses of microring resonators on YAGOI.

In this study, a numerical analysis of a compact microring resonator that was defined on a YAG-based thin film bonded on top of a SiO_2 cladding layer and operated at the wavelengths of 1.064 and 1.6 μm was performed. The full-vectorial finite-difference method was used to investigate the single-mode conditions of YAG waveguides at different waveguide sizes and their propagation losses at different SiO_2 cladding layer thicknesses. The key design parameters of the microring resonator, such as gap size and ring radius, were characterized in Lumerical Mode Solutions software (Ansys Canada Ltd., Vancouver, BC, Canada) based on the 2.5-dimensional variational finite-difference time-domain (2.5D varFDTD) method. By optimizing the gap size and the bending radius, a microring resonator with a high quality factor (Q -factor) and a wide free spectral range (FSR) was obtained.

resonator was etched on a YAG thin film that was bonded on top of a YAG substrate with an intermediate SiO_2 cladding layer. The microring structure consisted of a straight waveguide and a ring resonator. When light waves in the straight waveguide were on resonance with the ring, they first coupled into the cavity from the straight waveguide and then coupled out from the ring to the straight waveguide.

The full-vectorial finite-difference method was used to calculate single-mode conditions and propagation losses in straight waveguides and bending losses in bent waveguides at 1.064 and 1.6 μm . Maxwell's equations in a differential form were first used to conduct differential discretization based on the full-vectorial finite-difference time-domain (FDTD) method and then converted into a matrix form to solve waveguide modes [27]. The 2.5D varFDTD method was used to design and simulate a microring resonator with perfectly matched layer (PML) boundary conditions [28–30]. The 2.5D varFDTD is a direct space-time solution of Maxwell's equations for complex geometries. It works based on 2D FDTD by folding a 3D geometry into a 2D effective refractive index set. After Fourier transformation, the normalized transport, the Poynting vector, and the far-field projection were obtained [31]. PML boundaries could absorb the impacted electromagnetic energy on them, allowing the radiation to propagate out of the calculated area without interfering with the internal electric field [30]. The FSR and Q -factor were obtained by using 2.5D varFDTD method with mesh accuracy of 14 ppw (the number of mesh points per wavelength).

2 Device structure and methods

A schematic of the microring resonator is displayed in Figure 1, where x , y , and z directions are the reference directions of 2.5D varFDTD calculation. The microring

3 Results

To prevent signal distortion, single-mode conditions are critical for the transmission of optical signals. To achieve

Figure 1: Schematic of the microring resonator on YAGOI (inset: cross section of the YAG waveguide structure).

Table 1: Refractive indexes of YAG and SiO₂ at $\lambda = 1.064$ and $1.6 \mu\text{m}$

Material	Refractive index	
	$\lambda = 1.064 \mu\text{m}$	$\lambda = 1.6 \mu\text{m}$
YAG	1.8146	1.8062
SiO ₂	1.45	1.44

good confinement in the light field, waveguide dimensions were designed to satisfy single-mode operations; specifically, waveguide width (w) and film thickness (h) were set to less than an ultimate value. Table 1 presents the refractive indexes of YAG and SiO₂ at the simulation wavelengths of 1.064 and $1.6 \mu\text{m}$. Single-mode conditions at $\lambda = 1.064$ and $1.6 \mu\text{m}$ were first simulated.

The modal curves of YAG ridge waveguides with $0.7 \mu\text{m}$ width at $\lambda = 1.064 \mu\text{m}$ were first calculated. The dependence of the effective index on YAG waveguide thickness is illustrated in Figure 2(a). First-order transverse electric (TE) and transverse magnetic (TM) modes appeared at the YAG waveguide thicknesses of 0.9 and $0.92 \mu\text{m}$, respectively. The effective refractive index increased with the increasing YAG waveguide thickness. Figure 2(b) displays the dimensional cutting of TE and TM modes under single-mode and multimode situations. The bottom two lines represent boundary conditions for the occurrence of fundamental modes (TE and TM), whereas the top two lines denote boundary conditions for the occurrence of first-order modes. Considering the occurrence of only single-mode conditions, the selected values of YAG waveguide width and thickness

Figure 2: (a) Variation of the effective index as a function of YAG waveguide thickness at $\lambda = 1.064 \mu\text{m}$, (b) variation of cutoff dimension as a function of YAG waveguide width and thickness at $\lambda = 1.064 \mu\text{m}$, (c) variation of the effective index as a function of YAG waveguide thickness at $\lambda = 1.6 \mu\text{m}$, and (d) variation of cutoff dimension as a function of YAG waveguide width and thickness at $\lambda = 1.6 \mu\text{m}$ (insets in (b) and (d) present the simulated optical power distributions of YAG waveguides in TE and TM modes).

were limited to a range of the upper and lower curves. For example, when the YAG film thickness was $0.5\ \mu\text{m}$, widths required to perform single-mode operations in TE and TM modes were $0.50\text{--}1.12$ and $0.42\text{--}1.11\ \mu\text{m}$, respectively. Simultaneously, as the YAG film thickness increased, the width decreased to achieve single-mode conditions. The fundamental TE and TM modes optical power distribution for the YAG ridge thickness and width of 0.6 and $0.7\ \mu\text{m}$ at $\lambda = 1.064\ \mu\text{m}$ is presented in the inset of Figure 2(b). In the following simulation, the thickness and width of YAG ridge was selected as 0.6 and $0.7\ \mu\text{m}$ at $\lambda = 1.064\ \mu\text{m}$, respectively.

The modal curves of YAG ridge waveguides at $\lambda = 1.6\ \mu\text{m}$ were then plotted. In Figure 2(c), conditions for the appearance of TE and TM fundamental modes, first-order modes, and second-order modes at different waveguide thicknesses and $w = 1.0\ \mu\text{m}$ are expressed. For instance, first-order TE and TM modes appeared at the thicknesses of 1.42 and $1.44\ \mu\text{m}$, respectively, and the effective index increased with the increasing YAG film thickness. Figure 2(d) presents the cutoff dimensions of TM and TE modes under single-mode and first-order mode conditions. According to the range of the four curves, the appropriate width and thickness of YAG waveguides were selected to fulfill single-mode conditions. In the following calculation, we selected the width and thickness of the YAG waveguide to be 1 and $0.9\ \mu\text{m}$ at $\lambda = 1.6\ \mu\text{m}$, respectively. The fundamental TE and TM modes optical power distribution for $w = 1\ \mu\text{m}$ and $h = 0.9\ \mu\text{m}$ at $\lambda = 1.6\ \mu\text{m}$ is displayed in the inset of Figure 2(d).

The propagation losses of YAG waveguides ($h = 0.6\ \mu\text{m}$, $w = 0.7\ \mu\text{m}$) with different SiO_2 layer thicknesses (T) at $\lambda = 1.064\ \mu\text{m}$ are presented in Figure 3(a). The

propagation loss decreased as the SiO_2 layer thickness increased. Under the same SiO_2 layer thickness, the propagation losses in the TM mode were almost the same as those in the TE mode. YAG waveguide losses in TM and TE modes were less than $10^{-2}\ \text{dB/cm}$ when the SiO_2 layer thickness was greater than $2\ \mu\text{m}$. Figure 3(b) presents the propagation losses of YAG waveguides ($h = 0.9\ \mu\text{m}$, $w = 1.0\ \mu\text{m}$) with different SiO_2 layer thicknesses at $\lambda = 1.6\ \mu\text{m}$. When the SiO_2 layer thickness was greater than $3.0\ \mu\text{m}$, propagation losses in TE and TM modes were less than $10^{-2}\ \text{dB/cm}$.

A small bending loss is very important for the transmission of light in a microring. Figure 4 displays the relationship between the bending radius and bending loss of YAG ridge waveguides. At $\lambda = 1.064\ \mu\text{m}$, the width and thickness of YAG ridge waveguides were 0.7 and $0.6\ \mu\text{m}$, respectively. The bending loss decreased with the increasing ring radius, and the decreasing trend was relatively steep at the beginning. At $\lambda = 1.6\ \mu\text{m}$, the relationship between the bending loss and bending radius for YAG ridge waveguides ($h = 0.9\ \mu\text{m}$, $w = 1\ \mu\text{m}$) is illustrated. At the same ring radius, the bending loss at $\lambda = 1.6\ \mu\text{m}$ was greater than that at $\lambda = 1.064\ \mu\text{m}$.

The ring radius and the gap size between the ring and straight waveguides were the two main factors for the microring resonator. The gap size determined the coupling efficiency (k) of the input and output of the resonator. Coupling efficiency is defined as the proportion of the light energy entering the microring to the total input energy at a given wavelength. Figure 5(a) presents the coupling efficiencies for different gap sizes and the ring radius of $10\ \mu\text{m}$ at a wavelength near $1.064\ \mu\text{m}$. When the gap size exceeded $0.2\ \mu\text{m}$, the coupling efficiency of the

Figure 3: Propagation losses of YAG waveguides with different SiO_2 cladding layer thicknesses at (a) $\lambda = 1.064\ \mu\text{m}$ and (b) $\lambda = 1.6\ \mu\text{m}$.

Figure 4: Variation of bending loss with bending radius.

TE mode decreased rapidly with the increase of the gap size, whereas the coupling efficiency of the TM mode began to decrease when the gap size was greater than $0.15 \mu\text{m}$. The inset of Figure 5(a) displays the normalized transmission spectrum in the TE mode with a gap size of $0.15 \mu\text{m}$. It can be seen from the transmission spectra that the light of off-peak wavelength does not meet the resonance requirement, and the resonance cannot occur in the microring, whereas the light with wavelength at the peak point enters into the microring by satisfying the resonance conditions [32]. At wavelength near $1.6 \mu\text{m}$, the relationship between gap size and coupling efficiency for the ring radius of $15 \mu\text{m}$ is presented in Figure 5(b). The coupling efficiency began to decline steeply when the

gap size was greater than $0.3 \mu\text{m}$. The inset of Figure 5(b) displays the normalized transmission spectrum in the TE mode with a gap size of $0.2 \mu\text{m}$.

It is well known that a small ring radius can reduce the dimensions of a microring and improve device integration; however, bending also causes a nonnegligible bending loss. Hence, ring radius and bending loss should be considered carefully during the design of a microring. The Q -factors and FSR values of the single-mode microring with different gap sizes and ring radii were calculated at both wavelengths. The quality factor, Q , is an important parameter to characterize the device performance, which is the ability to measure the energy storage and frequency selection of the optical resonant cavity. The Q -factor of the microring resonator is calculated by the following equation [33]:

$$Q = \frac{\lambda_0}{\Delta\lambda_{\text{FWHM}}}, \quad (1)$$

where λ_0 is the resonance wavelength and $\Delta\lambda_{\text{FWHM}}$ is the full bandwidth at half maximum of the transmitted power. With the increase of Q value, the linewidth of laser becomes narrower, and the possibility of laser oscillation is greater. The relationship between the Q -factor and the coupling efficiency k could be expressed as follows [34]:

$$Q = \frac{\pi n_g L}{\lambda} \frac{\sqrt{A(1-k^2)}}{1-A(1-k^2)}, \quad (2)$$

where L is the microloop circumference and A is the loss coefficient. As shown in Figure 5, in the case of fixed ring radius, the value of k is directly affected by the gap sizes. According to equation (2), there is a nonlinear

Figure 5: Variations of coupling efficiency with gap size around (a) $\lambda = 1.064 \mu\text{m}$ and (b) $\lambda = 1.6 \mu\text{m}$ (insets in (a) and (b) present the normalized transmission spectra corresponding to the marked circles).

relationship between Q value and coupling efficiency (k). With the gap size increased, the mutual coupling effect between the microring and the direct waveguide became smaller; thus, the Q -factor increased.

For the YAG microring ($w = 0.7 \mu\text{m}$ and $h = 0.6 \mu\text{m}$), the Q -factor increased with the increase of the gap size and the ring radius at $\lambda = 1.064 \mu\text{m}$ (Figure 6(a)). When the ring radius was less than $10 \mu\text{m}$, the Q -factor increased significantly with the increase of the ring radius; however, when the ring radius was greater than $10 \mu\text{m}$, the Q -factor remained unchanged. The Q -factor of the TE mode was found to be higher than that of the TM mode at the same gap size and ring radius. The propagation loss of the microring was affected by the following factors: (1) radiation loss due to waveguide bending and (2) leaking of a portion of the electromagnetic field to the YAG substrate when light passed through the microring resonator. As the microring radius increased, the bending loss of waveguides decreased (Figure 4); thus, the Q -factor became larger.

At $\lambda = 1.6 \mu\text{m}$, the relationship among the Q -factor, ring radius, and gap size ($h = 0.9 \mu\text{m}$ and $w = 1.0 \mu\text{m}$) is illustrated in Figure 6(b). As the ring radius increased, the Q -factor first increased and then remained unchanged at radii greater than $20 \mu\text{m}$. The Q -factor increased with the increase of the gap size, and the Q -factor of the TE mode was larger than that of the TM mode. Furthermore, in practice, the structure will contain residual roughness of the waveguide etched surface, which results in scattering losses. The Q -factor will reach a maximum value and may decrease as the ring radii increases because of the scattering loss.

Figure 7: FSR values of the microring resonator at different ring radii.

FSR is defined as the separation between two adjacent resonant wavelengths. For different resonant wavelengths, the FSR values of the microring were calculated as follows:

$$\text{FSR} = \frac{\lambda^2}{n_g \cdot L}, \quad (3)$$

where $n_g = n_{\text{eff}} - \frac{\lambda \partial n_{\text{eff}}}{\partial \lambda}$ is the group effective refractive index and L is the microring circumference [34]. Equation (3) expresses that FSR is inversely proportional to the effective refractive index and the ring radius and proportional to the square of the wavelength.

The relationship between FSR and ring radius at λ around 1.6 and 1.064 μm is presented in Figure 7, which

Figure 6: Q -factors of the microring resonator for different ring radii and gap sizes around (a) $\lambda = 1.064 \mu\text{m}$ and (b) $\lambda = 1.6 \mu\text{m}$.

Figure 8: (a) Schematic of a dual-channel straight waveguide microring structure. Transmission spectra of the microring (drop port) with 15 μm radius, (b) around the wavelength of 1.064 μm and gap size of 0.15 μm and (c) around the wavelength of 1.6 μm and gap size of 0.2 μm.

is exactly consistent with the result of equation (3). In both TE and TM modes, the maximum FSR was obtained at the smallest ring radius ($R = 5 \mu\text{m}$), and FSR decreased with the increasing ring radius. Furthermore, at λ around 1.6 μm, the difference between TM and TE curves was significant and FSR values at the same ring radius were greater than those at λ around 1.064 μm. Figure 8(b) and (c) exhibits the normalized transmission spectra of the drop port of the microring resonator with two straight waveguides (radius = 15 μm) at λ around 1.064 and 1.6 μm, respectively. The specific structure of the microring is shown in Figure 8(a). It can be seen that the linewidth of the TE mode was narrower than that of the TM mode. At the wavelength of 1.064 μm, the linewidth of TE mode was 0.142 nm, and that of TM mode was 0.309 nm. The linewidth of the transmission spectra were 0.780 nm (TM) and 0.388 nm (TE), respectively, when the wavelength was 1.6 μm. The FSR for the microring were about 6.5 nm (TE) and 6.72 nm (TM) at λ around 1.064 μm, whereas the values were about 14.62 nm (TE) and 15.68 nm (TM), respectively, at λ around 1.6 μm.

4 Conclusion

A numerical analysis of a microring resonator defined on a YAG thin film was conducted. Based on the full-vectorial finite-difference method, single-mode conditions and propagation losses of YAG waveguides were calculated. The h , w , and T of ridge waveguides were optimized to 0.6, 0.7, and 2 μm at $\lambda = 1.064 \mu\text{m}$, whereas the values were optimized to 0.9, 1.0, and 3.0 μm at $\lambda = 1.6 \mu\text{m}$. The Q -factor and FSR of the microring resonator were calculated by using 2.5D varFDTD method. The effects of different gap sizes and ring radii on the Q -factor and FSR of the microring resonator were discussed. The Q -factor increased with the increase of the gap size and the ring radius, and FSR decreased with the increasing bending radius. This study will be useful for the fabrication of integrated YAG microlaser sources.

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