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Analysis of Temperature Dependence of Ce:YIG for Athermal Waveguide Optical Isolator

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Abstract: The temperature dependence of optical properties of magneto-optic garnet Ce:YIG was analyzed for the athermal operation of the Mach-Zehnder interferometer (MZI) optical isolator composed of an SOI-based waveguide with a Ce:YIG upper cladding layer. By measuring the wavelength shift of transmittance due to temperature changes, the temperature dependences of the refractive index and magneto-optic coefficient of Ce:YIG were characterized to be 2.5×10^{-4} K^{-1} and 13 deg/cm/K, respectively. We discuss the design of an athermal waveguide optical isolator.

Introduction: A waveguide isolator is indispensable for integrated photonic circuits to realize the high-speed modulation and highly coherent operation of laser diodes. We have investigated Mach-Zehnder interferometer (MZI) based waveguide optical isolator and circulator having high optical isolation and wide operation bandwidth.[1,2] These devices are composed of a silicon-on-insulator (SOI) based photonic waveguide with a magneto-optic garnet upper cladding layer integrated using a surface activated direct bonding technique. The transmittance of MZI-based devices exhibits quasi-sinusoidal wavelength dependence. A temperature change causes the wavelength shift of transmittance characteristics due to the temperature dependences of refractive index (dn/dT) and magneto-optic coefficient ($d\theta_F/dT$). dn/dT of Si and SiO_2 are well-known at the telecom wavelength. However, dn/dT and $d\theta_F/dT$ of magneto-optic garnet Ce:YIG are unknown. In this report, in order to realize an athermal waveguide optical isolator, we investigate the dn/dT and $d\theta_F/dT$ of Ce:YIG by measuring the wavelength shift in transmittance of the MZI optical devices.

MZI-based nonreciprocal devices: Figure 1 shows a schematic of MZI-based optical isolator with silicon waveguides. The MZI has nonreciprocal and reciprocal phase shifters. The nonreciprocal phase shifter provides a phase differences of $-\pi/2$ and $+\pi/2$ depending on the light propagation direction due to a magneto-optic effect. The reciprocal phase shifter provides a phase difference independently of the propagation direction by the asymmetric path length of MZI arm. In the transmitting direction, input light interfere constructively and is coupled to the output. On the other hand, in the isolating direction, the light launched into the device shows anti-phase interference and is radiated away from side ports. An MZI-based 4-port optical circulator can be formed by using 3 dB couplers having a 2×2 port configuration. The circular operation is achieved, since the in-phase and anti-phase interferences select the output path in a nonreciprocal manner.

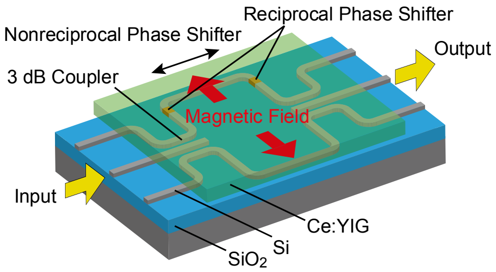

Fig. 1: Schematic of MZI based optical isolator with silicon waveguides.

Experimental results: The transmittance of isolator and circulator changes quasi-sinusoidally as a function of wavelength. With large asymmetry in the path difference between two arms, the free spectral range (FSR) of MZI interference becomes narrow and a noticeable wavelength dependence of a reciprocal phase difference $\pi/2+2m\pi$ (m: integer) is introduced. The wavelength shift in transmittance characteristics due to temperature changes is clearly observed in a measureable wavelength range. In this study, we fabricated an MZI circulator with a path difference of 44.7 μm, which corresponds to a reciprocal phase difference of m=66 at λ=1550 nm. The transmission spectrum of the circulator was measured using an amplified spontaneous emission light source and an optical spectrum analyzer thorough a fiber-to-fiber configuration. The temperature of the circulator was controlled from 10 °C to 75 °C using a sample stage equipped with a Peltier unit. Measured isolating wavelengths are plotted in Fig. 2 as a function of temperature. Blue and red plots correspond to adjacent isolating wavelengths with an FSR of 15 nm. Without applying magnetic field, the spectra in

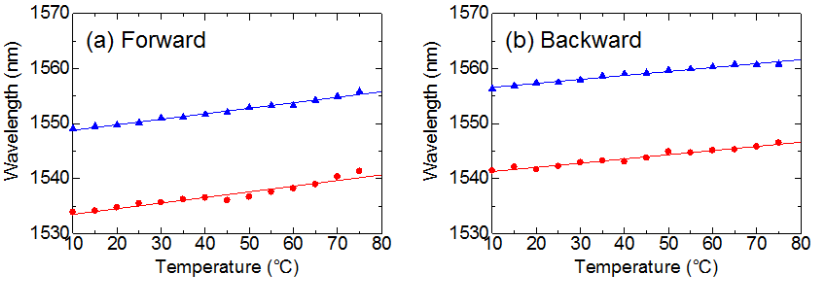

Fig. 2: Measured shift of isolating wavelengths in MZI circulator due to temperature change.

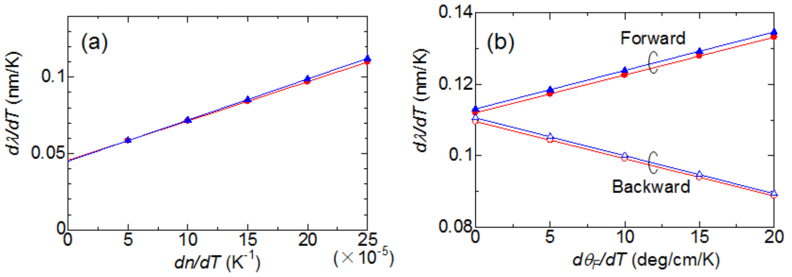

Fig. 3: Simulated wavelength shift as a function of dn/dT and dθ_F/dT of Ce:YIG.

forward and backward directions were identical due to the absence of the magneto-optic effect. By applying magnetic field, the transmission peak in the forward direction coincides with the transmission bottom in the backward direction.

Analysis of temperature dependence: Firstly, the transmission spectra was simulated by an optical mode solver using refractive indexes of Si, SiO_2, and Ce:YIG at room temperature. Then, dimensions of the Si core are corrected so that the simulated FSR agrees with measured one. Secondly, the wavelength shift due to temperature changes was simulated using dn/dT=1.86×10^{-4} K^{-1} and 1.0×10^{-5} K^{-1} for Si and SiO_2, respectively,[3] as a function of dn/dT of Ce:YIG as shown in Fig. 3(a). Since the slope of the measured wavelength shift without applying magnetic field was 0.11 nm/K, dn/dT of Ce:YIG is estimated to be 2.5×10^{-4} K^{-1}. The nonreciprocal phase shift was simulated by a perturbation theory using the Faraday rotation coefficient of Ce:YIG.[4] The wavelength shift due to temperature changes was simulated as a function of $d\theta_F/dT$ as shown in Fig. 3(b). Since the slope of the measured wavelength shift with magnetic field applied was 0.13 and 0.10 nm/K in the forward and backward directions, $d\theta_F/dT$ of Ce:YIG is estimated to be 13 deg/cm/K for θ_F= □3536 deg/cm at room temperature.

Conclusions: By measuring the wavelength shifts of an MZI nonreciprocal device, the temperature dependences of refractive index and Faraday rotation coefficient of Ce:YIG were analyzed to be 2.5×10^{-4} K^{-1} and 13 deg/cm/K, respectively. Increase in refractive index at high temperature results in an increase in a reciprocal phase difference. The Faraday rotation is decreased at high temperature, which results in a decrease in a nonreciprocal phase difference. Therefore, if we choose proper waveguide dimensions and the length of reciprocal phase shifter, deviations in nonreciprocal and reciprocal phase differences due to temperature changes are cancelled in the backward direction. Then, the athermal operation of a waveguide optical isolator is expected. For example, when the cross-sectional Si waveguide dimension is 550 nm × 220 nm and the length of reciprocal phase shifter is 4.3 µm, the wavelength shift due to a temperature change from -10 °C to 60 °C is expected to be less than 0.081 nm at [illegible]=1550 nm..

References

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