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Tunable Lithium Niobate Waveguide Loop

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***Abstract*—A novel, compact, and tunable lithium niobate (LN) planar waveguide loop structure composed of two Y junction reflectors is proposed for optical and radio frequency signal processing applications. The preliminary device shows a high quality factor of 6.5×10^4, due to the low propagation loss of the titanium-diffused LN waveguide. The tunability of the loop by electric field is estimated.**

***Index Terms*—High quality (Q) factor, lithium niobate (LN) waveguide, resonator, tunable loop.**

I. Introduction

LOW-LOSS waveguide loop or ring structures have received much interest for applications in coherent and incoherent optical signal processing, such as optical or radio-frequency (RF) filtering, switching, and modulation. Passive or active loops have been realized in material structures such as glass waveguide, polymethylmethacrylate (PMMA) waveguide, GeO_2-doped silica waveguide [1], and optical fibers. [2] However, the resonance frequency in these ring structures generally cannot be tuned conveniently. For instance, some of them can be tuned thermally, however, the tuning speed and accuracy are not sufficient for high-speed applications.

In this letter, we propose and demonstrate a novel planar loop structure that consists of two titanium (Ti)-diffused lithium niobate (LN) interconnection waveguides and two Y junction reflectors. To our knowledge, this is the first time that a planar loop structure is demonstrated using the Ti-diffused waveguide. Compared with a discrete LN disk resonator that typically relies on prisms to couple light in and out of the loop [3], this monolithic waveguide resonator can result in more stable coupling. In comparison with the traditional circular loop, the present device using the Y junction reflectors is more compact and the bending loss associated with the circular loop can be avoided. The latter has been a concern for the weakly guided Ti-diffused LN waveguide.

By exploiting the electrooptic property of LN, the resonance frequency of the loop can be readily tuned via an applied electric field. The tuning speed and accuracy can be much improved over those obtained via thermal tuning. Such a ring structure is expected to have extensive and promising optical and RF applications. For example, as an optical coherent resonator, it can be used as an optical comb filter or tunable channel add–drop filter for dense wavelength-division-multiplexed (DWDM) communication systems. Due to its unique phase characteristics, the loop, as a tunable all-pass filter, has also good applications in chromatic dispersion compensation of high-speed DWDM systems [4]. It also can function as an incoherent optical delay line in an infinite impulse response optical RF filter [5]. Furthermore, if the passive waveguide is replaced by a waveguide with optical gain, such as an Er-doped Ti-diffused waveguide with optical pumping [6], the loop structure can operate as a ring laser. More complex resonator structures could be built based on this loop structure.

This letter is organized as follows. First, the device structure is described. Second, the preliminary measurement result is presented and the optimal condition to achieve the optimal filtering effect is discussed. The wavelength tunability property of the loop structure is estimated theoretically.

II. Device Structure and Operation Principle

An initial device was made at Sumitomo Osaka Cement Company using z-cut LN. Fig. 1(a) depicts the schematic top view of the structure. A picture of the device is shown in Fig. 1(b). The device is composed of one straight-through waveguide coupled to a loop structure, which is made of two Y junction reflectors connected to two waveguide branches. The Y junction reflector, with gold-coated total reflection mirror, can guide light from one arm totally to the other arm. Each reflector has a ~1.0-dB loss.

The coating is applied only to the end facet of the Y junction and not to the straight-through waveguide. For each end, a small piece of LN is glued at the top to support the coating of waveguide facet. Input light is coupled to the straight waveguide and then onto the loop. The coupling coefficient is determined by 1) the effective modal index of the waveguide, 2) the length of the coupling region, and 3) the gap between the straight-through waveguide and the adjacent interconnecting waveguide of the loop. For our current device, the gap is ~4.2 μm; the length of the straight-through waveguide is 14 mm; the separation between the upper and the bottom arm of the loop is around 100 μm. Therefore, one round-trip in the loop is close to 28 mm. The chip shown in Fig. 1(b) has an area of 14 mm × 1.8 mm.

A theoretical model of the loop has been previously established [7], [8]. The loop is considered as a coupler connected with the waveguides. The complex amplitudes of the electric fields, E_{in} and E_{out} for the straight-through waveguide and E_{c1} and E_{c2} for the coupler, as depicted in Fig. 1(a), are related by [8]

$$E_{\text{out}} = \sqrt{1-\gamma_1}(\sqrt{1-\kappa}E_{\text{in}} - j\sqrt{\kappa}E_{c2}) \quad (1)$$

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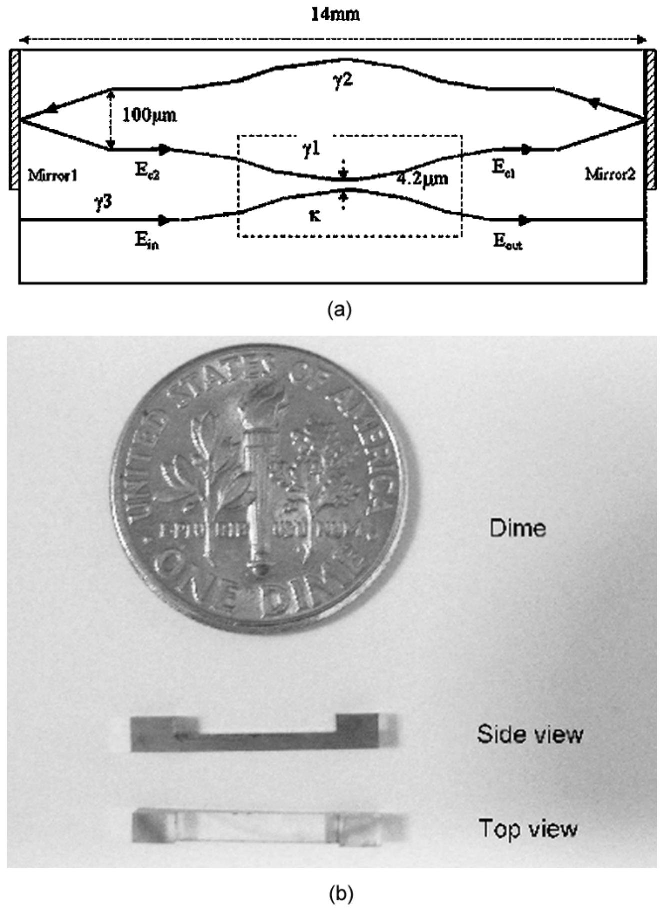

Fig. 1. (a) Schematic top view of the LN-loop (not to scale). (b) Top and side views of the device.

$$E_{c1} = \sqrt{1-\gamma_1}(-j\sqrt{\kappa}E_{\rm in} + \sqrt{1-\kappa}E_{c2}) \quad (2)$$

$$E_{c2} = E_{c1}\sqrt{1-\gamma_2}{\rm Exp}(-j2\pi nL/\lambda) \quad (3)$$

where κ is the optical intensity coupling coefficient of the coupler area, γ_1 is the optical intensity loss of the coupler, γ_2 is the optical intensity loss at the part of loop outside the coupling area, including the reflection loss of Y junctions and the propagation loss of the waveguide loop, L is the length of the loop, n is the refractive index of the optical mode, and λ is the wavelength of the laser light.

For the transmission characteristics, we note

$$\frac{E_{\rm out}}{E_{\rm in}} = \frac{\sqrt{1-\kappa}\sqrt{1-\gamma_1} - (1-\gamma_1)\sqrt{1-\gamma_2}e^{-j2\pi nL/\lambda}}{1-\sqrt{1-\kappa}\sqrt{1-\gamma_1}\sqrt{1-\gamma_2}e^{-j2\pi nL/\lambda}} \quad (4)$$

and the fiber-to-fiber optical intensity transmission is

$$T = (1-\gamma_3)\left|\frac{E_{\rm out}}{E_{\rm in}}\right|^2 \quad (5)$$

where γ_3 includes the optical intensity coupling loss between the fiber and the LN waveguide, and the propagation loss of the straight-through waveguide except for the coupling region.

III. Results and Discussion

Preliminary transmission measurement at different wavelengths, ranging from 1.5545 to 1.5550 μm, is done using a tunable laser that is transverse-magnetic polarized. The periodic transmission is shown in Fig. 2, together with the fitting curve predicted by (5) using $\kappa = 92.5\%, \gamma_1 = -1.1$ dB, $\gamma_2 = -2.4$ dB, $\gamma_3 = -4.6$ dB, and the optical path length $n \times L$ of 61 740.0 μm. This implies that the total internal loss for the loop, including the Y junction reflection loss and waveguide propagation loss, is on the order of 3.5 dB. The measured quality (Q) factor defined by $Q = \lambda/(\Delta\lambda)_{\rm FWHM}$, [7] is measured at $\sim 6.5 \times 10^4$. To increase the Q value further, one can use an active waveguide, such as Er-doped LN waveguide, to compensate for the internal loss.

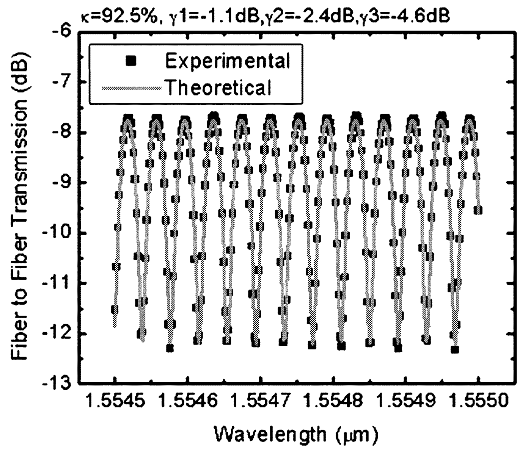

Fig. 2. Transmission versus wavelength measurement (dots) of the sample and curve fitting (solid line).

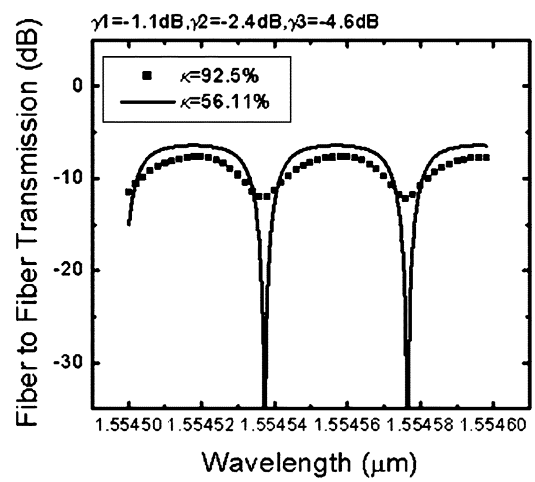

Fig. 3. Transmission at two coupling coefficients.

From (4), the optimal value of the coupling coefficient κ is given by

$$\kappa = 1 - (1-\gamma_1)(1-\gamma_2). \quad (6)$$

With $\gamma_1 = -1.1$ dB, $\gamma_2 = -2.4$ dB, the optimal κ is, thus, 56.11%. However, the coupling coefficient for the preliminary device is found to be ~92.5%, which is much larger than that the optimal value. A large coupling coefficient reduces the extinction ratio of the transmission. Fig. 3 plots the transmission curves for two cases of the coupling coefficient, 92.5% and 56.11%, assuming other parameters remain the same. With the

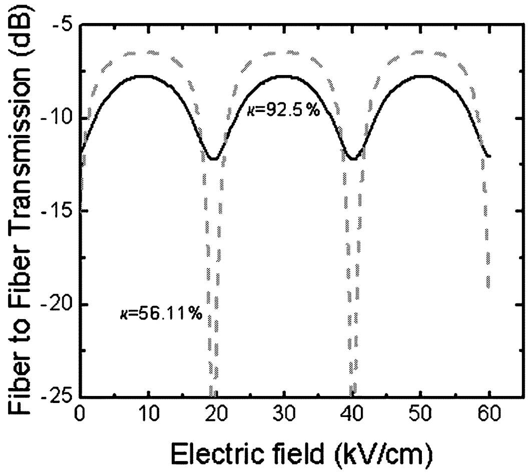

Fig. 4. Tunability of the loop as a function of the electric field for two different coupling coefficients.

optimized coupling coefficient, the extinction ratio can be much larger than that observed in Fig. 2 for large κ, and the output light can become very small when the phase-matching condition of the loop is met.

By incorporating an electrode along the waveguide loop, the device can be made frequency tunable. This is due to the electrooptic property of LN. For this case, we assume the zero-field refractive index of the Ti-diffused waveguide is $n_e = 2.14$, and the linear variation of the index is given as [9]

$$\Delta n_e = -\frac{1}{2} n_e^3 r_{33} E_z \tag{7}$$

where r_{33} is electrooptic coefficient of LN, set at 30.9 pm/V, and E_z is the electric field. Fig. 4 plots the transmission as a function of the electric field, assuming the electrode has an effective length of 5 mm and the optical wavelength is 1.5545 μm. As shown in Fig. 4, the transmission can be periodically tuned by the applied electric field, with a period ∼20 kV/cm. For the case of the optimized coupling coefficient of 56.11%, the output is changed from the peak of −6.45 dB to theoretically zero with an electric field swing of 10 kV/cm. This implies potential applications of the tunable loop for switching or fast modulation.

IV. Summary

We have demonstrated a novel, compact, and planar LN waveguide loop that has low loss ∼3.5 dB, and high Q factor of $\sim 6.5 \times 10^4$. The loop performance is consistent with the estimated coupling coefficient between the loop and the straight-through waveguide, and can be improved by reducing the coupling coefficient. By exploiting the inherent electrooptic property of LN, the loop can be wavelength tunable which is a desirable property for communication and signal processing applications.

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