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Reconfigurable Optical Delay Lines Based on Single Folded Waveguides

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We propose a novel single folded waveguide-based reconfigurable optical delay line. Due to waveguide self-coupling, light travels back and forth along the waveguide, forming resonances. With two phase shifters embedded in the waveguide, resonance modes and coupling can be conveniently controlled. Under proper phases, the delay line can be reconfigured to perform various types of delays. In particular, when the resonance input and mutual coupling strengths are properly matched, the group delay dispersion can be significantly reduced, favoring an optical signal delay with low distortion. The group delay can be continuously tuned at low tuning power by changing the phases.

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I. INTRODUCTION

Slow light has attracted much research interest in recent years due to its wide range of applications in controllable optical delay lines, optical buffers for telecommunication systems, and true time delay methods for synthetic aperture radars [1–3]. Various physical mechanisms can be used to generate slow light [3], including electromagnetically-induced absorption in atomic vapors, stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) in fibers and planar waveguides, exciton absorption and four-wave mixing in semiconductor optical amplifiers (SOAs), photonic crystal waveguides, and resonant photonic structures. Among the above structures, resonant structures on silicon platforms are the most attractive due to their compact size and compatibility with the complementary metal-oxide-semiconductor (CMOS) technologies [4–8].

Here, we propose a novel reconfigurable optical delay line to realize continuous group delay tuning. Figure 1 shows the schematic structure of our proposed device, which is essentially a single waveguide folded to form three directional couplers. Because of the waveguide's self-coupling, light travels back and forth in the waveguide, and as a result, the group delay increases. There exist forward (large blue arrows) and backward (small red arrow) resonance loops in the device, as indicated in Fig. 1. The light's backward coupling is induced by the inner Mach-Zehnder Interferometer (MZI) coupler. Two sets of push-pull phase shifters are embedded in the waveguide for phase tuning.

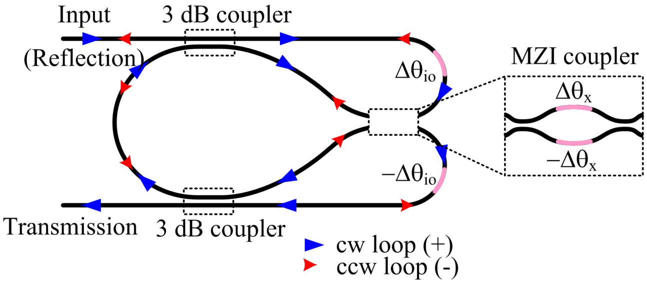

Fig. 1. (Color online) Schematic of the reconfigurable optical delay line structure consisting of a single folded waveguide.

II. MODELING AND DISCUSSION

We use the transfer matrix method to analyze our device optical characteristics [9]. The transfer functions for the transmission and the reflection ports in the z-domain are given by

$$\begin{aligned} H_t(z) &= t_{wg}t_x\frac{t_{io}-t_x(t_{io}^2+1)az^{-1}+t_{io}a^2z^{-2}}{1-2t_xt_{io}az^{-1}+(\kappa_x^2+t_x^2t_{io}^2)a^2z^{-2}}, \quad (1)\\ H_r(z) &= e^{-i\Delta\theta_{io}}t_{wg}\kappa_x \\ &\times \frac{1-2t_xt_{io}az^{-1}+z^2z^{-2}}{1-2t_xt_{io}az^{-1}+(\kappa_x^2+t_x^2t_{io}^2)a^2z^{-2}}, \quad (2)\end{aligned}$$

where $t_{io}=\cos(\Delta\varphi_{io})$ and $\kappa_{io}=\sin(\Delta\varphi_{io})$ are the resonator input/output effective transmission and coupling

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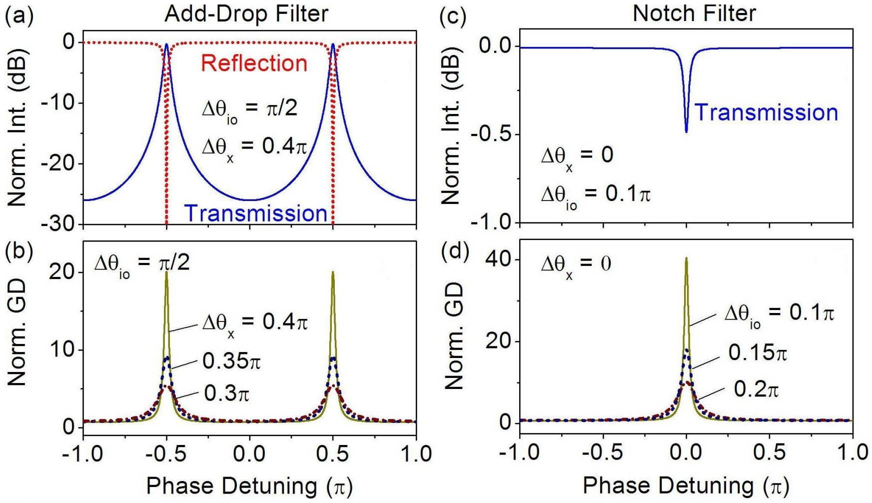

Fig. 2. (Color online) Normalized intensity and group delay (GD) responses for the device reconfigured as an add-drop filter and a notch filter.

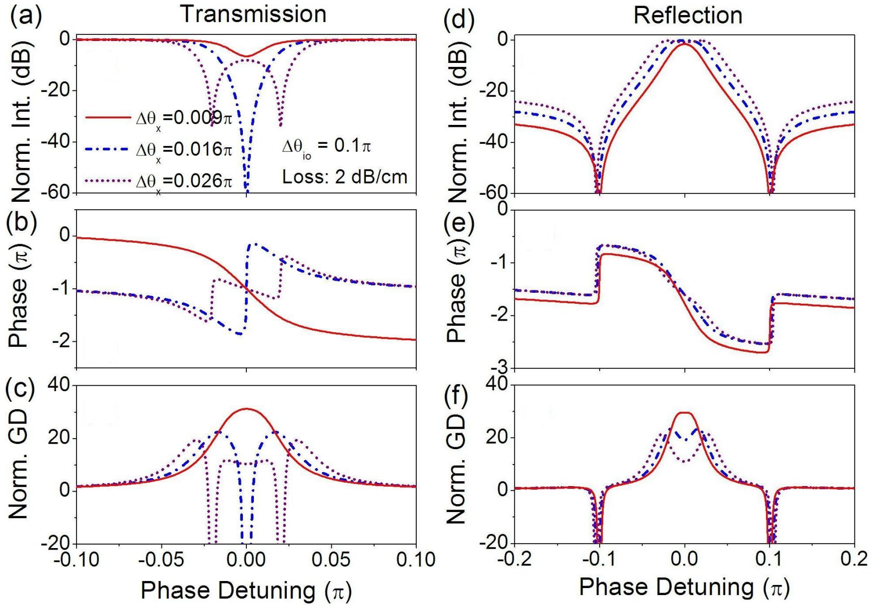

Fig. 3. (Color online) Normalized intensity, phase and group delay responses for the transmission and the reflection ports.

coefficients, $t_x = \cos(\Delta\varphi_x)$ and $\kappa_x = \sin(\Delta\varphi_x)$ are the effective resonator mutual-mode transmission and coupling coefficients, $z^{-1} = \mathrm{e}^{-i\Delta\varphi}$ is the unit delay in z-domain, $\Delta\varphi$ is the phase detuning, a is the loss factor (a = 1 for the lossless case), t_{wg} is the electric field transmission factor directly from the input to the transmission port.

The device can be reconfigured to perform various types of functions by tuning $\Delta\theta_{io}$ and $\Delta\theta_x$. In particular, we consider the following four representative cases. (1) When $\Delta\theta_{io} = 0$, the ratio of the magnitudes of the transmission and the reflection transfer functions is $|\mathrm{H}_t(z)|/|\mathrm{H}_r(z)| = t_x/\kappa_x$, which is virtually a splitter where its splitting ratio is controllable by $\Delta\theta_x$. (2) When $\Delta\theta_x = \pi/2$, $\mathrm{H}_t(z) = 0$, implying all light is reflected back; thus, the device acts as a reflector. (3) When $\Delta\theta_{io} = \pi/2$, the transfer functions are analogous to the through- and the drop-port transfer functions in a micro-ring add-drop filter (ADF). The effective waveguide-resonator coupling coefficient is t_x, which can be controlled by $\Delta\theta_x$. (4) When $\Delta\theta_x = 0$, the transmission-port transfer function is analogous to the micro-ring resonator notch filter (NF) transfer function. The effective waveguide-resonator coupling coefficient is k_{io}, which can be controlled by $\Delta\theta_{io}$. There is no resonance generated in the first two configurations; thus, the group delay is caused by the waveguide itself and is relatively small. Figure 2 shows the normalized intensity and group delay responses for the last two configurations as filters. We assume a loss factor of a = 0.9986 (corresponding to a 2 dB/cm waveguide loss) in the calculation. Note that the ADF configuration has a FSR two times that for the NF configuration. An enhanced group delay, whose magnitude and bandwidth can be tuned by $\Delta\theta_x$ or $\Delta\theta_{io}$, is observed around the resonances.

Although the group delay can be enhanced by using a single uncoupled resonance, the group delay dispersion (GDD) around the resonance is large, usually causing distortion in the delayed signal. In our device, when $\Delta\theta_x$ and $\Delta\theta_{io}$ are properly set, the device can be reconfigured as a coupled resonance structure, exhibiting second-order filter characteristics with increased bandwidth and low GDD.

Figure 3 shows the transmission and the reflection responses for various $\Delta\theta_x$'s with a fixed $\Delta\theta_{io}$. The transmission and the reflection resonance line shapes are determined by the relative values of $\Delta\theta_{io}$ and $\Delta\theta_x$. When $\Delta\theta_x$ is small, the backward coupling is relatively weak, and the device works in the over-coupling regime. Normal phase dispersion occurs around the resonance, and slow light is expected at the transmission port. When $\Delta\theta_x$ is large, the backward coupling is relatively strong, and the device works in the under-coupling regime. The resonance is split into two. Anomalous phase dispersion occurs around the split resonances, and fast light is expected at the transmission port. However, for the reflection port, slow light always occurs on resonance. In particular, when the resonance input and mutual coupling strengths are properly matched, the third-order GDD can be eliminated at the resonance frequency, and the group delays have flat-top spectral responses. The delay magnitude can also be continuously tuned by changing $\Delta\theta_{io}$ and $\Delta\theta_x$ simultaneously.

III. CONCLUSION

In conclusion, we proposed a novel reconfigurable optical delay line using a single folded waveguide. Due to the waveguide self-coupling, forward and backward resonance loops are formed, and transmission and reflection ports exhibit distinct group delay characteristics. By tuning the critical phases in the waveguide, the delay line can be reconfigured to perform various functions, including direct transmission and reflection, and single and coupled resonance-based filtering. Therefore, various tunable delays can be produced from these reconfigured elements. As long as the phases are properly matched, the high order group delay dispersion around the resonance can be greatly reduced, with an increased group delay bandwidth, which, as a result, favors optical signal delay with high fidelity.

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