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Optical delay lines using coupled slab waveguides and ring resonator with a negative refractive index core

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ABSTRACT

Total delay time of a structure composed of a slab waveguide coupled with a ring resonator where negative refractive index material is replaced in the core of the structure is investigated in this work. In this paper, a two-port ring resonator (TPRR) which is made of a core with negative refractive index has been used to generate a time delay for a Gaussian-shaped pulse with 1 GHz bandwidth. It is shown that the creation of the ring how causes more n_g of a straight waveguide and results are compared with positive refractive index core TPRR. We have used metamaterial to make an $n<0$ media and have used two cascaded metamaterial rings to increase the bandwidth.

1. Introduction

Optical delay structures are one of the important sections of optical processing systems in the optical communication networks. Optical tunable delay lines are used in applications such as equalizers, synchronizers, correlators, logic gates and multiplexers [1]. Some examples of optical delay line structures are based on electromagnetic induced transparency (EIT) [2], photonic crystals [3], quantum dot semiconductor optical amplifier [4], erbium-doped optical fiber [5], plasmonic waveguides [6] and ring resonators [7]. Except delay lines, ring resonators can be used as filters [8] and multiplexers [9] in all optical telecommunication systems.

In this paper, we propose an optical delay unite composed of a slab waveguide in coupling with a ring resonator, where negative refractive index material is replaced in the core of the structure. Investigation of properties of the negative refractive index media by Veselago returns to 1968 [10]. However, demonstration of negative refractive index by metamaterials and photonic crystals accomplished in the end of 90s decades [11]. Firstly, Smith et al. demonstrated simultaneously $\varepsilon<0$ and $\mu<0$ in a given range of frequency by metamaterial [12]. Metamaterials are artificial materials with the capability of tuning ε and μ, which yields special properties such as negative refractive index can be used in antenna efficiency increment [13], lens resolution improvement [14] and positive and negative slow light in waveguides [15]. Waveguides with metamaterial core [16] or cladding [17], can produce slow light in a given range of frequencies because of poynting vectors in their boundaries. In recent years, semiconductor metamaterial structures have been emerged enables applications of these structures in optical integrated devices [18].

2. Straight and ring waveguides with negative refractive index core

In this section, we investigate guiding properties of slab and ring waveguides with a core of metamaterial. First, we utilize straight symmetric slab waveguide with a core refraction of index of ($n_{\text{core}}=-2.6$) to create a delay line. Dispersion relation for transverse electric (TE) modes in a slab waveguide is given in [19]. Effective refractive index (n_{eff}), group refractive index (n_g) and delay time (t_d) are given as below:

$$n_{eff}\,\omega = c\beta \tag{1}$$

$$n_g = n_{eff} + \omega\frac{dn_{eff}}{d\omega} \tag{2}$$

$$t_d = \frac{L_{eff}.n_g}{c} \tag{3}$$

where ω, β, c and L_{eff} are the angular frequency, the propagation constant, the speed of light in vacuum and the effective length of

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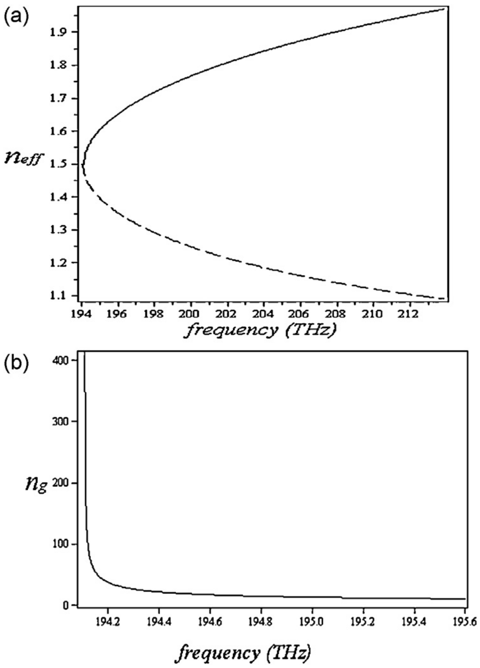

Fig. 1. (a) n_{eff} of the forward (solid line) and backward (dashed line) wave and (b) n_g of the forward wave for a slab waveguide for TE$_2$ mode. The core thickness is $d = .255$ μm, $\mu_{\text{core}} = \varepsilon_{\text{core}} = -2.6$ and $\mu_{\text{cladding}} = \varepsilon_{\text{cladding}} = 1$.

the waveguide, respectively. Here, we plot n_{eff} and n_g using dispersion relation for TE$_2$ mode for a straight waveguide, then we will examine the effects of ring creation on these quantities, accordingly.

Fig. 1(a) represents n_{eff} of the forward (solid line) and backward (dashed line) wave and Fig. 1(b) represents n_g of the forward wave for a slab waveguide with core thickness of $d = 0.255$ μm and $\mu_{\text{core}} = \varepsilon_{\text{core}} = -2.6$. In all figures, we use TE$_2$ mode and $\mu_{\text{cladding}} = \varepsilon_{\text{cladding}} = 1$, $L = 5.5$ mm. For this waveguide, we can obtain either positive (forward wave) or negative (backward wave) group index. Although core and cladding refractive indices do not vary with frequency, but n_{eff} changes rapidly near the frequency of $f = 194.108$ THz where n_g becomes large according to Eq. (2).

Fig. 1(b) demonstrates that this waveguide can be applied for a single frequency electromagnetic wave trapping and delaying near the frequency $f = 194.108$ THz, but near this frequency it does not fit a Gaussian pulse with a normal spectral width as a delay line due to the large variations of n_g around this frequency. If this waveguide be used to guide a Gaussian pulse centered on $f = 194.108$ THz, will experience large distortions. For higher frequencies ($f > 194.2$ THz), the pulse shape will be almost unchanged, but in this range of frequencies n_g is low. We assume the spectral width of Gaussian pulses is 1 GHz. In order to choose an optimum frequency range for this Gaussian pulse propagation with minimum deformation, we define normalized detuning parameter S using n_g diagram as:

$$S = \frac{n_{g,\max} - n_{g,\min}}{n'_g} \tag{4}$$

where n'_g is

$$n'_g = \frac{n_{g,\max} + n_{g,\min}}{2}. \tag{5}$$

Here, regarding the required bandwidth for pulse propagation includes minimum distortion and with linear group index variation, we found out that $S < 0.02$ by using trial and error method. In Fig. 1(b) in a frequency range of 194 THz $< f <$ 196 THz, the $39.9 < n_g < 40.634$, for a pulse with $\Delta\omega = 3$ GHz width, is linear and $S = 0.018$. For a waveguide with $L = 5.5$ mm length, group delay difference between lower and upper frequencies of the propagating pulse is 0.013 ns ($0.731 < t_d < 0.744$ ns). There is a direct relation between delay time and waveguide length L_{eff} according to Eq. (3). Thus to get additional delay time, L_{eff} has to be increased, which cause more space occupation by straight waveguide as a delay block in an optical processor. Therefore, we use a coupled straight waveguide-ring resonator structure to increase n_g [20], where this structure enhances n_g, and occupies small space.

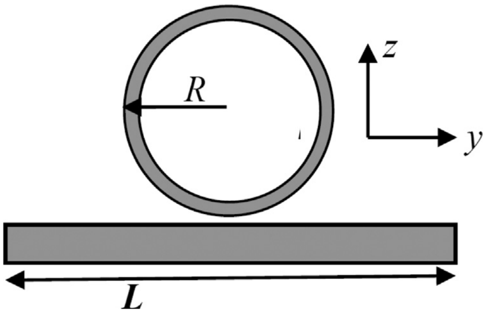

Fig. 2. Two port ring resonator with infinity in y-direction.

A two-port ring resonator (TPRR) [20] is indicated in Fig. 2. Both straight and ring are made of slab waveguides and are assumed to have infinite length in the y-direction. Parameters τ and κ are respectively through and cross-port amplitude coupling constants of the directional coupler. Total group index for a coupled straight waveguide-ring resonator structure is given by [20]:

$$n_g = n_{g,\text{straight}} + \frac{2\pi r n_{g,\text{ring}}}{L} \times \frac{(1-\tau^2)\gamma[\gamma(1+\gamma^2) - (1+\gamma^2)\tau\cos(2\pi r\beta_{\text{ring}})]}{(\tau^2 - 2\gamma\tau\cos(2\pi r\beta_{\text{ring}}) + \gamma^2)(\tau^2\gamma^2 - 2\gamma\tau\cos(2\pi r\beta_{\text{ring}}) + 1)} \tag{6}$$

In Eq. (6), we replaced n_{eff} of paper [20], with n_g in our calculations. For a lossless structure $\gamma = 1$, but structure has bent loss and in all of this paper we get $\gamma = 0.99$.

According to [20,21] for a coupled straight waveguide-ring resonator structure with $R = 383$ μm and L approximately 14 times larger than ring's radius, $n_{g,\text{ring}} \approx n_{g,\text{straight}}$. Regarding this, Fig. 3(a) demonstrates the ratio of group index using Eq. (6) per group index of a straight waveguide. As can be seen from this figure, depending on the propagating pulse bandwidth, different group indices will be achieved. The total value of n_g can be enhanced using cascaded rings. Fig. 3(b) shows delay time for a 1 GHz pulse with $\tau = 0.29$. Maximum delay time occurs in $f = 194.186$ THz and is 1.33 ns, where the delay time for the straight waveguide in this frequency is 0.738 ns. In a structure with lower ring radius and τ, the bandwidth will be increased [9].

Fig. 4 illustrates n_g for a straight waveguide with $\varepsilon_{\text{core}} = \mu_{\text{core}} = 2.6$ and $d = 0.495$ μm for getting max n_g near 194.2 THZ. We can see that the second term of the Eq. (3) is negligible. The time delay for this waveguide with $R = 382.9$ μm, $\tau = 0.29$ is demonstrated in Fig. 5 where the maximum delay is 0.115 ns.

Comparison between Fig. 5 and Fig. 3b shows that in rings with the same radius and τ, the delay time in $n_{\text{core}} = -2.6$ TPRR is more than $n_{\text{core}} = 2.6$. Another difference between them is the role of the straight waveguide at high delay times. In $n_{\text{core}} = 2.6$ multi ring resonator, the straight waveguide does not have a significant effect on the delay time and bandwidth of the system. We can say that the rings generate delay time but in $n_{\text{core}} = -2.6$ rings, straight waveguide plays an active role in the generation of the delay time and bandwidth; hence the straight waveguide length has to be chosen properly.