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Micro-ring resonator based all-optical reconfigurable logic operations

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ABSTRACT

An all-optical reconfigurable logic operation essentially constitutes a key technology for performing various processing tasks with ultrafast signal-processing technologies. We present designs and simulations for highly cascadable all-optical reconfigurable logic operations using GaAs–AlGaAs micro-ring resonator based optical switches and multiplexers. The switching action of the ring resonator is achieved through variation in the refractive index of the ring resonator produced by the two-photon absorption (TPA) effect through the application of optical pump pulse. The proposed circuit can perform any of the four digital logic operations (NOT, NOR, XOR, AND) by using the appropriate optical pump signal at the selection port of the multiplexer. We have tried to exploit the advantages of micro-ring resonator based all optical switch to design an all-optical circuit. The reconfigurable nature of the circuit offers maximum flexibility for the end user since the entire application can be changed simply by adjusting the multiplexer select line signals. Numerical simulation confirming described methods is given in this paper.

1. Introduction

The development of broadband telecommunication networks requires all-optical technologies in order to avoid optoelectronic conversions and overcome electronic bottlenecks. This trend has stimulated the rapid evolution of optical networking technologies in recent years [1,2]. In high-speed optical communication, high-speed all-optical logic gates [3–8] are expected to play an important role in switching, signal regeneration, data processing, etc. [9–11] to realize all-optical functions. In recent years, all optical logic gates have been demonstrated and reported on several different schemes, including semiconductor optical amplifier (SOA) [12–19], Mach–Zehnder interferometer (MZI) [20–24], semiconductor laser amplifier (SLA) loop mirror [25,26], ultrafast nonlinear interferometers [27,28], four-wave mixing process in SOA [29,30] or cross gain (XGM) or cross phase (XPM) modulation [31], highly nonlinear fibers (HNLF) [32], periodically poled lithium niobate (PPLN) [33].

Optical nonlinear materials (ONLM) provide a major support to optical switching based all-optical logic and algebraic processing [34–40]. The nonlinear characteristics are the basics to implement and have delivered efficient results at high bit rates. The average pump power required for HNLF is nearly 25 mW [32]. Also one of the limitations of HNLF is stimulated Brillouin scattering (SBS), which sets an upper limit of power, which can be launched into the HNLF. The SBS threshold power (P_{th}) determines the maximum obtainable nonlinear phase shift. The average pump power required for SOA varies from 0.8 mW to 100 mW for different purposes [41,42]. But because of the slow carrier recovery process in the SOA, their pattern effects would be highly dependent on the operation bitrate. The average pump power required for periodically poled lithium niobate (PPLN) is nearly 100 mW [33]. Also the disadvantages of PPLN are thickness of 0.5 mm and lower damage threshold are needed. Recent advances in micro-fabrication technology has made it possible to fabricate compact micro-ring resonators with small radius and a very high quality factor using tightly confined semiconductor channel waveguides [43,44]. In this paper we have tried to exploit the advantages of special nonlinear characteristics of ring resonator [45–50] like reduced switching threshold [51,52], ultra-compactness and small size, which can lead to high device integration densities and ultra-high speed for designing time division multiplexing schemes which will work in the all-optical domain [53,54]. Moreover, the use of a critically coupled resonator allows higher switching contrast. Previously most existing circuits have been constructed to perform a single function, but recent technologies suggest that devices may also be able to perform multiple logic operations.

Recently, reconfigurable logic gates have attracted much interest of the research communities due to its flexibility for networking operations and potential low cost. The reconfigurable all-optical logic gate combines some existing technologies and some new innovations together to achieve its novel functionality. Previously reported techniques for achieving the all optical reconfigurable logic functions mainly utilized semiconductor optical amplifiers (SOAs) [55,56], quantum-dot semiconductor optical amplifiers [57]. Although, SOAs show high gain and are compact and integratable, the performance of SOA-based logic gates is

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controlled by the SOA's intrinsic slow gain recovery time, which limits the speed of operation. Reconfigurable optical logic unit can be designed with a terahertz optical asymmetric demultiplexer and electro-optic switches [58]. Micro-ring resonator is also used to design reconfigurable optical directed-logic circuits using the electro-optic method [59].

In this paper, we proposed a reconfigurable logic gate with the help of all optical multiplexer based on the nonlinear property of micro-ring resonator. Different logic operations including AND, XOR, NOR and NOT gates are successfully realized using a single device and under the same input operating conditions. The reconfigurability between the four logic operations was achieved solely by adjusting the select lines of the multiplexer.

The paper is organized as follows: Section 2 provides the structural detail and operating principle of all optical switches using the micro-ring resonator. The theory and design of the all optical multiplexer circuit is presented in Section 3. The theory, design and simulation results and discussion of the proposed scheme for an all optical reconfigurable logic circuit are presented in Section 4, followed by conclusion

2. Micro-ring resonator based optical switch

The basic micro-ring-resonator (MRR) consists of unidirectional coupling between a ring resonator and input-output waveguides. This basic configuration can mainly be divided into three building blocks: the ring resonator, the input–output bus waveguide(s) and the input–output coupler(s). The ring resonator can act as an optical reservoir to accumulate the power at a particular wavelength, called resonant wavelength, corresponding to the phase condition in resonance for constructive interference. The working function of the optical ring resonators are the same as Fabry–Perot (FP) resonators. In contrast to the FP resonator, the ring resonator does not require any additional mirrors or reflecting facets for optical feedback. When light is passed through the ring from input waveguide, it builds up in intensity through multiple round-trips due to constructive interference at the resonant wavelength. At resonance, the drop port shows maximum transmission and through port shows a minimum transmittance. The amount of light which couples in and out of the ring is determined by the input–output couplers. If the resonator is made of a non-linear material, a logic switch can be produced [60–65]. The change in effective refractive index induced by the high intensity pump beam depends largely on the nonlinear property of the material used. When a strong optical control (pump) pulse and a weak probe light are coupled into the ring resonator through resonance, the control pulse generates free carriers in the ring resonator due to the two-photon absorption (TPA) effect. A green laser ($\lambda = 532$ nm) is used from top of the ring to pump the ring as shown in Fig. 1(a). The generated free carriers reduce the refractive index of GaAs–AlGaAs through the plasma dispersion effect and cause temporarily blue-shift of the ring resonances. The output power of the probe light is modulated by the resonance shift. The resonant wavelength and the transmission of the probe light relax back after the control pulse leaves due to the fast surface recombination of the free carriers. Hence the MRR acts an optical switch and the status of the switch is controlled by the optical pump pulse.

The simple model of a single ring resonator is shown in Fig. 1(b). The circumference of the ring is L ($=2\pi r$, r is the radius of the ring), k_1 and k_2 are the field coupling coefficient between the input & the ring and is the field coupling coefficient between the ring and the output bus respectively, α is the intensity attenuation coefficient of the ring, the intensity insertion loss coefficient of the directional coupler is γ. We assume E_{i1} and E_{i2} are the input and add port field respectively and E_t and E_d are the through port and drop port field respectively. We also assume the fields at the points a, b, c and d are E_{ra}, E_{rb}, E_{rc} and E_{rd} respectively as shown in Fig. 1(b).

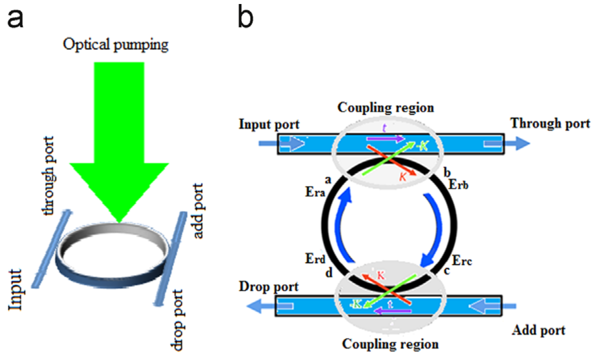

Fig. 1. (a): Optical pumping process. (b): Single ring resonator.

From Fig. 1(b), the field E_{ra}, E_{rb}, E_{rc}, E_{rd} can be written as [66–69]

$$E_{ra} = (1-\gamma)^{1/2}\left[j\sqrt{k_1}E_{i1} + \sqrt{(1-k_1)}E_{rd}\right] \tag{1}$$

$$E_{rb} = E_{ra}\exp\left(-\propto\frac{L}{4}\right)\exp\left(jk_n\frac{L}{2}\right) \tag{2}$$

$$E_{rc} = (1-\gamma)^{1/2}\left[j\sqrt{k_2}E_{i2} + \sqrt{(1-k_2)}E_{rb}\right] \tag{3}$$

$$E_{rd} = E_{rc}\exp\left(-\propto\frac{L}{4}\right)\exp\left(jk_n\frac{L}{2}\right) \tag{4}$$

where, $k_n = \frac{2\pi}{\lambda}n_{eff}$ is the wave propagation constant, λ is the wavelength of the light source, n_{eff} is the effective refractive index$=n_0+n_2I=n_0+\frac{n_2}{A_{eff}}P$, where n_0 and n_2 are the linear and non-linear refractive indexes respectively. I and P are the intensity and power of the optical pump signal. A_{eff} is the effective cross sectional area of the ring resonator.

The fields at the through port and drop port can be written as [66–69]

$$E_t = (1-\gamma)^{1/2}[\sqrt{(1-k_1)}E_{i1} + j\sqrt{(k_1)}E_{rd}] \tag{5}$$

$$E_d = (1-\gamma)^{1/2}[\sqrt{(1-k_2)}E_{i2} + j\sqrt{(k_2)}E_{rb}] \tag{6}$$

Solving Eqs. (1)–(6), we get the through port and drop port fields as

$$\begin{aligned} E_t = {} & \frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}x^2\exp^2(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i1} \\ & + \frac{-D\sqrt{k_1}\sqrt{k_2}x\exp(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i2} \end{aligned} \tag{7}$$

$$\begin{aligned} E_d = {} & \frac{-\sqrt{k_1}\sqrt{k_2}Dx\exp(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i1} \\ & + \frac{D\sqrt{1-k_2} - D\sqrt{1-k_1}x^2\exp^2(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}x^2\exp^2(j\phi)}E_{i2} \end{aligned} \tag{8}$$

where,

$$D = (1-\gamma)^{1/2}, \quad x = D\exp\left(-\alpha\frac{L}{4}\right), \quad \phi = \frac{k_nL}{2}$$

The above equations help to design a ring resonator as a switch and the above non-linear characteristics of micro-ring resonator is utilized for designing a tree-net architecture in all-optical domain and can successfully be exploited for time division all-optical data multiplexing scheme which is the basic building block of the all optical reconfigurable logic circuit.