Optik 125 (2014) 4529–4533

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

An all-optical switch/photodetection at 1550 nm, based on a micro-ring resonator array

A. Rostami [a,*], M.H. Mohammadzadeh [b], M. Dolatyari [a], G. Rostami [a]

[a] School of Engineering-Emerging Technologies, University of Tabriz, Tabriz 5166614761, Iran
[b] Department of Electrical Engineering, Islamic Azad University, Ahar Branch, Ahar, Iran

ARTICLE INFO

Article history:
Received 9 August 2013
Accepted 20 February 2014

Keywords:
Micro-ring resonator
Photodetector
Optical nonlinear effects
All-optical switch
Resonance wavelength

ABSTRACT

In this paper, a photodetector based on InGaAs micro-ring resonator array with 5 μm radius, in telecommunication wavelength region has been investigated. Then for the first time to our knowledge, with the change of refractive index due to optical nonlinear effects (such as: Kerr effect, two photon absorption, free carrier dispersion and free carrier absorption), an all-optical switch, based on pump-probe configuration using this photodetector have been proposed. So, the suggested device, will introduce a dual functionality that is important from view point of economically purposes and in term of integration. By numerically solving the light propagation equations, with FDTD and Crank–Nicolson methods, in addition to steady state and transient response, also we have found the frequency response, in both configurations. With increasing reverse bias voltage, and optimizing the free carrier transportation from absorption region, switching frequency can be increased up to 200 GHz. Also by optimal choosing of parameters such as the number of rings and spaces between two adjacent rings and so on, the box-like spectral response of photodetector with high efficiency is achievable.

1. Introduction

In recent years, due to the increasing demand for more bandwidth from users, WDM systems have a special and important place in optical telecommunication. In this system, multiple message signals with different wavelengths through a single optical fibre are sent to the destination [1]. At the receiver, the received signal after amplification, are separated by wavelength filters and then using various photodetectors such as: MSM-PD, PIN-PD, APD-PD, DDR-PD, UTC-PD, WG-PD, TW-PD, VM-PD [2–4] and so on, the message light beams are converted to, electrical signals which can be used in the subsequent controlling and processing devices [5].

Recently, to reduce the cost and size of the systems, instead of using the aforesaid photodetectors with a filter, the resonance cavity enhancement photodetectors (RCE-PDs) due to their high efficiency and tunable filter behaviour have been used [6–13]. However, these detectors, due to their requirement to accurate design of the DBR mirrors and the complex and expensive fabrication technology, are not suitable for optical telecommunication systems [14,15]. So, single-ring resonator based photodetectors are presented [15–20]. These detectors in addition to selective and tunable spectral response and high efficiency and low dark current, have small size and low fabrication cost [21]. The main problem of these photodetectors is their narrow and Lorentzian-Shape spectral response that requires precise control of micro-ring resonance wavelength and transmitted signal wavelength [14,22]. Fabrication of micro-ring resonators with accurate radii, and precise control of the signal wavelength in lossy transmission line, is a very difficult and costly work [22]. In this paper, using a parallel array of compact micro-ring resonators, the box-like (flat top–steep edge) spectral response is obtained.

Then, based on the change in refractive index due to optical nonlinear effects (such as Kerr effect, TPA, FCA and FCD effects), which causes a blue shift in ring resonance wavelength [23], the all-optical switch in the ring photodetector structure based on pump-probe configuration are discussed. This structure introduces a dual-Functional device (switch and detector), that is useful from viewpoint of economically reasons and in terms of integration.

Also, since the frequency response of an all optical switch based on ring resonator is depended to the carrier lifetime [24], by optimizing the carrier transmission time from the depletion region (with increasing reverse bias voltage), the switching speeds increases 10 times compared to the previous structures [24,25].

* Corresponding author.
E-mail addresses: rostami@tabrizu.ac.ir (A. Rostami), mh-mohammadzadeh@iau-ahar.ac.ir (M.H. Mohammadzadeh).

http://dx.doi.org/10.1016/j.ijleo.2014.02.013

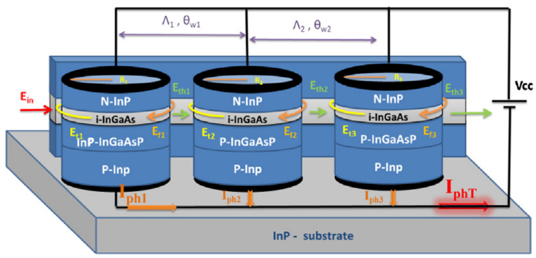

Fig. 1. Schematic diagram of three-ring resonator based photodetector.

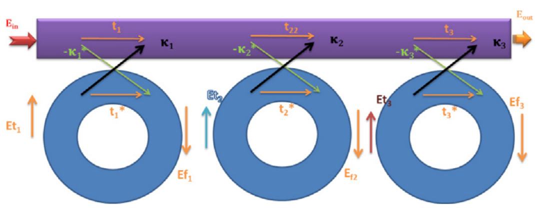

Fig. 2. Optical model for the switch-detector structure.

2. Theory

To better understand the presented structure in this paper, a schematic of triple-ring resonator based photodetector, are shown in Fig. 1.

As can be seen, in this configuration, signal beam (E_{in}) is entered to the straight waveguide, then if the input wavelength is matched with 1st ring resonance wavelength, with assuming critical coupling condition; maximum part of the light is coupled to the ring. The coupled light will circulate and resonate and accumulate in the ring and if the photon energies are higher than bandgap of materials in absorption layer ($E_{\text{g-InGaAs}}$), the light beam is absorbed to the ring absorption region and creates the electron-hole-pair (EHP). These created free carriers at the presence of electrical field in the depletion region (due to reverse bias voltage), moved towards external circuits. Otherwise if there is no match between 1st ring resonance wavelength and input beam wavelength, the light will move to the 2nd ring and this story repeated to nth ring. The combination of output currents from all of the rings, create total photocurrent (I_{phT}). At the presence of pump beam, the displayed structure in Fig. 1, will work as a switch device for probe beam. For investigating the switching and light detecting behaviour of the above structure, we used the presented model in Fig. 2 [26,27].

According to Fig. 2, the coupling between two adjacent rings is eliminated. With a lossless coupling and single-mode light propagation assumptions, the relations between input optical beam (E_{in}), circulating field (E_r) and output field from nth ring resonator (E_{thn}) are calculated as follows [26–28]:

$$E_{r_n}(t) = r_n E_{t_n}(t) - ik_n e^{i\beta_{w(n-1)}\Lambda_{(n-1)}} E_{th_{(n-1)}}(t) \quad (1)$$

$$E_{th_n}(t) = r_n e^{i\beta_{w(n-1)}\Lambda_{(n-1)}} E_{th_{(n-1)}}(t) - ik_n E_{t_n}(t) \quad (2)$$

And optical beam after one round trip inside the ring resonator is:

$$E_{t_n}(t) = E_{r_n}(t-\tau) e^{i\beta_n L r_n} e^{-\Gamma\alpha_{0n} L r_n} \quad (3)$$

In the case of switch configuration, similar equations are written for the input optical pump beam ($E_{in\text{-}P}$), circulating pump ($E_{r\text{-}p}$) and output pump ($E_{th\text{-}p}$) [28].

In these equations, κ, $n \ni \{2,3,4,\ldots,\infty\}$, r, κ, Λ, β_w, are the ring number, field coupling and transmission coefficients between the straight and ring waveguides, space between two adjacent ring and propagation constant in straight waveguide and $\beta = 2\pi n_r/\lambda$, τ, Γ, α_0, $L_r = 2\pi R$, R, represents the propagation constant in ring resonators, round trip time of the ring resonator, confinement factor, propagation loss inside the micro-ring in μm^{-1}, ring waveguide perimeter and ring radius respectively. Relationship between the coupling and transmission coefficients is:

$$|r_n|^2 + |k_n|^2 = 1 \quad (4)$$

To determine distribution of the circulating optical field (E_{rs}) inside the micro-ring resonator, in presence of nonlinear effects (such as: Kerr effect, FCD, FCA and TPA), in the photodetector configuration, we used from the following “modified nonlinear Schrodinger equation” [28]:

$$\frac{\partial E_{rs}(z,t)}{\partial z} + \frac{n_0}{c}\frac{\partial E_{rs}(z,t)}{\partial t} = -\frac{\alpha_0}{2}E_{rs}(z,t) - \left(\frac{\alpha_2}{2} - in_2k_0\right) I_{r(A+B)}(z,t)E_{rs}(z,t) - \left(\frac{\Delta_{fc}}{2} - i\Delta n_{fc}k_{0n}\right) E_{rs}(z,t) \quad (5)$$

and in the case of switch configuration, the interaction between circulating pump and probe beam (E_{rpr}, E_{rpu}) is calculated from following Eq. (6) [28].

$$\frac{\partial E_{rpr}(z,t)}{\partial z} + \frac{n_0}{c}\frac{\partial E_{rpr}(z,t)}{\partial t} = -\frac{\alpha_0}{2}E_{rpr}(z,t) - \left(\frac{\alpha_2}{2} - in_2k_0\right) I_{rpu}(z,t)E_{rpr}(z,t) - \left(\frac{\Delta_{fc}}{2} - i\Delta n_{fc}k_{0n}\right) E_{rpr}(z,t) \quad (6)$$

$$\frac{\partial E_{rpu}(z,t)}{\partial z} + \frac{n_0}{c}\frac{\partial E_{rpu}(z,t)}{\partial t} = -\frac{\alpha_0}{2}E_{rpu}(z,t) - \left(\frac{\alpha_2}{2} - in_2k_0\right) I_{rpu}(z,t)E_{rpu}(z,t) - \left(\frac{\Delta_{fc}}{2} - i\Delta n_{fc}k_{0n}\right) E_{rpu}(z,t) \quad (7)$$

In these equations we assume that, the circulating pump intensity is very higher than probe light field ($E_{rpu} \gg E_{rpr}$) [24].

In which $\Delta\alpha_{fc}$ and Δn_{fc} are the changes in the absorption and refractive index due to free carriers generated by TPA and linear absorption processes which are proportional to the free-carrier density (N_{fc}) that calculated from below equation [28]:

$$\frac{dN_{fc}}{dt} = \frac{\alpha_0 I}{h\nu} + \frac{\alpha_2 I^2}{2h\nu} - \frac{N_{fc}}{\tau_{fc}} \quad (8)$$

In this relation, 1st, 2nd and 3rd term are due to linear absorption, TPA and heat losses processes respectively and α_n, τ_{fc}, h, ν, I represents TPA coefficient, free carrier life time, plank's constant, input pump photons frequency and circulating field intensity respectively. The width of depletion region, in the $P^+N^-P^+$ photodiode in the nth ring is [29]:

$$w_n = \sqrt{\frac{2\varepsilon_n V_{cc}}{eN_{dn}}} \quad (9)$$

In which V_{cc} is applied reverse bias voltage to the pin diode, N_d is donor concentration in the mid layer, e is electron charge and ε_n is dielectric constant. The dark electric field across the depletion region in the nth ring is [29]:

$$Ed_n = -\frac{eNd}{\varepsilon n}(w_n - x) \quad (10)$$

The change in the concentration of created EHPs in the absorption layer of nth ring, due to moving carriers towards the external circuit (caused by dark electric field) are expressed by the following