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Transient and steady state analysis of micro ring resonator array based photodetector in optical communication wavelength (linear and nonlinear operation)

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ABSTRACT

Array of micro ring resonators based optical photodetectors is introduced and evaluated in this paper to operate in optical communication windows for broad band situation. In this work, we introduced an array of resonators to engineer the transfer function of the detector for broad band operation as well as very sharp edges. The electron and photon transport in the proposed structure is modeled based on rate equation and then transient and steady state behavior are extracted. Finally nonlinear operation added to the model and its effect on spectral behavior as well as transient operation is investigated.

1. Introduction

Wavelength division multiplexing (WDM) is a good approach to acknowledge basic demand on bandwidth enhancement in optical communication. In this system information modulated on carriers in different central wavelengths and submitted through fiber channel and in the end of channel for separation of different channels one has to use optical narrowband filters [1,2]. An optical fast detector as well as large efficiency is one of basic component in optical communications. BEP for conventional photodetectors such as PIN, APD, MSM and etc. is small and there is trade-off between efficiency and bandwidth [3]. There are a lot of proposals to obtain high bandwidth as well as high efficiency. Based on these studies structures such as WGPD, RCEPD, and MRWPD and materials such as Si, Ge, III–V compounds such as InGaAs, InP, etc. can be pointed out [4–9]. Usually waveguide based photodetectors (WGPD) has high efficiency and bandwidth because of side coupling of light optical path and carrier transport path is orthogonal together and then efficiency and bandwidth can be managed separately [10]. So, the proposed structure has high BEP but WGPDs has ability to operate in broad spectrum range and optical filters can be used to separate channels well. This is a main problem that the structure has and integration is hard and has high cost [3]. RCEPD photodetectors have high efficiency as well as suitable bandwidth. Also, selectable spectrum is another advantage of this structure and also it does not need to use WDM filters [3–6,11,12]. But operation of this system needs to design precisely DBR mirrors that are expensive to make. Also, it need standing wave effect and depends on incident wave angle that is not suitable to use in optical communications [5,13]. Micro ring resonators are compact and able to select wavelengths that are used in filters and detectors design [7–9,14–16]. For removing all limitations due to low efficiency and non-tunability of conventional detectors at 2006 and 2008 photodetectors based on ring resonators proposed and fabricated [8,9]. Micro ring resonators based photodetectors use advantages of both WGPD and RCEPD to prepare selective spectral response and have large BEP. A basic problem in these structures is Lorentzian spectral response. So, because of narrow band spectral response if laser source has a small oscillation then detector response is changed strongly. According to this spectral response a small wavelength shift is tolerable and needs to tune wavelength precisely. Also, having a smooth leading and trailing edges concludes to introduce considerable cross talk between channels. In 2011 a new structure based on RCEPD for obtaining box like spectral response was introduced [17]. For the proposed structure in [17] quantum efficiency and 3-dB bandwidth are 51.161% and 0.26 nm and 0.4 nm respectively. This structure

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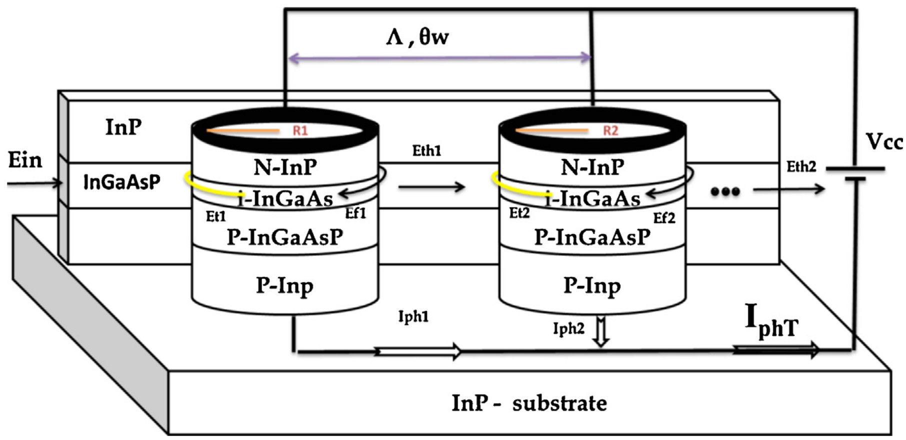

Fig. 1. Schematic of photodetector based on Micro Ring Resonators.

due to low efficiency and band width as well as complex fabrication process is not suitable for optical communications. Such box like spectral response can be observed from devices made by array of micro ring resonators [18–22]. Box like spectral response of these structures can be manipulated by gap between resonators, coupling efficiency, radius of resonators, number of rings and arrangement of the structure. In 2012 the idea of using micro ring resonators in photodetectors in optical communications was presented [22]. In this research from transparent and passive Silicon based micro ring resonators operating at 1550 nm optical communication wavelength for filtering and wavelength selection operation used. Light absorption is made by PIN photodetector fabricated on a resonator by III–V compounds. Using optimized parameter the proposed photodetector has efficiency about 98.2% in pass band of 0.5 nm. Also, compared to RCEPD structure the proposed structure is compatible to integrate and low price. But using heterostructure photodetector in DWDM system, in presence of small oscillation in laser source a large oscillation in output signal is observed [23]. The proposed structure has a narrow bandwidth and usually cannot be used as band pass filter. In the past research [7–23] reports main concentration was on linear operation, but because of resonance in micro ring resonators nonlinear effects such as Kerr-effect, Two-photon absorption, free carrier dispersion and absorption is considerable [24]. In this paper, with considering nonlinear effects, a homogeneous photodetector based on micro ring resonators in optical communications windows as well as large bandwidth that able to work as multi channel WDM photodetector is discussed. The proposed structure has constant value in pass band and a steep leading and trailing edges. The proposed structure has a large efficiency as well as suitable band width. At first a model for analysis of optical fields in micro ring resonators is proposed and then equations for optical fields in micro ring resonators and carrier transport in depletion layer are derived and finally using finite difference numerical method we try to solve those. Transient and steady state solution for the proposed structure in both linear and nonlinear regimes in optimized case is extracted and demonstrated.

2. Theoretical background

In Fig. 1 schematic of the photodetector based on microring resonators in the form of PIN converter is illustrated. As it can be seen in left hand the incident electric field of optical signal is coupled to straight waveguide. If the optical frequency is near to ring resonator resonance frequency the incident signal coupled to the ring and one observe that resonance is occurred.

This field hold inside the ring and finally absorbed by InGaAs semiconductor based PIN photodetector. If the incident optical signal frequency is far from ring resonator resonance frequency, the optical signal through direct optical waveguide without coupling propagates to the next ring resonator position. This situation is repeated for the second and third ring resonators. Finally we can detect outgoing optical signal through output port of the direct waveguide. Top view of the photodetector is illustrated in Fig. 2. [25] For the case of single mode waveguide and ring resonators with lossy coupling, mathematical modeling for the photodetector is given as follows [26,27].

According to demonstrated graph in Fig. 2, the following equations can be written to manage optical fields in different part of the system. In Eq. (1), different fields components for the first coupler are related together.

$$E_{r1} = r_1 E_{t1} - i\kappa_1 E_{in} \tag{1}$$

In this equation r_1 and κ_1 are transmission and coupling coefficients respectively. Also, E_{r1}, E_{t1} and E_{in} are circulating field in the ring, output field from the ring and incident field in input waveguide respectively.

In Eq. (2), the output field in the waveguide is related to the other fields in the coupler.

$$E_{\text{th}1} = r_1 e^{i\beta_1 L_{C1}} E_{\text{in}} - i\kappa_1 E_{t1} \tag{2}$$

In Eqs. (3) and (4), similar to Eqs. (1) and (2) output fields in the ring and waveguide are related to other fields and system parameters. In this equation Λ is distance between rings. Also, r and k are the coupler transmission and coupling parameters respectively.

$$E_{r2} = r_2 E_{t2} - i\kappa_2 e^{i\beta_{W1}\Lambda_1} E_{\text{th}1} \tag{3}$$

$$E_{th2} = r_2 e^{i\beta_{W1}\Lambda_1} E_{th1} - i\kappa_2 E_{t2} \tag{4}$$

For the ring number n we can generalize the output fields in terms of fields and system parameters that are illustrated in Eqs. (5) and (6).

$$E_{rn} = r_n E_{tn} - i\kappa_n e^{i\beta_{W(n-1)}\Lambda_{(n-1)}} E_{th(n-1)} \tag{5}$$

$$E_{thn} = r_n e^{i\beta_{W(n-1)}\Lambda_{(n-1)}} E_{th(n-1)} - i\kappa_n E_{tn} \tag{6}$$

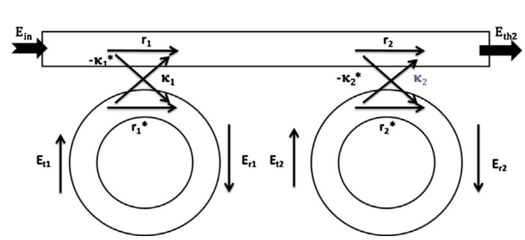

Fig. 2. Top view of the two ring based photodetector.