Microring-Based Resonant Cavity Waveguide Photodetectors for WDM Optical Systems

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ABSTRACT
Analytical models for bandwidth and bandwidth-efficiency product (BEP) of microring waveguide photodetectors (MRWPDs) are presented. In addition to carrier transport and charging processes, the photon lifetime effect is included in the bandwidth model. This effect is characterized by the ODB of microring resonators. It is shown that the short cavities and partially overcoupled structures are suitable for very high speed photodetection. Meanwhile, photon lifetime can be set to obtain terahertz selective photodetectors. Also, a novel CMOS compatible silicon MRWPD is introduced and its high speed performance is investigated. It is shown this photodetector can provide BEP in order of several tens gigahertz even with very low absorption and low volume (about 2 μm^3) active regions.
Keywords: bandwidth, photodetectors, optical waveguide, microring resonators, integrated optics, resonant-cavity-enhanced (RCE).

1. INTRODUCTION

Resonant cavity enhanced photodetectors (RCEPDs) provide high quantum efficiency along with a high speed and narrow spectral response [1]. However, they have rarely been used in long-wavelength optical communication and most of their potential has not been utilized in this important and economical field. Recently, we have proposed microring waveguide photodetectors (MRWPDs) which are new category of RCEPD and recognized as RCE-waveguide photodetectors (RCE-WGPDs) [2-3]. The MRWPDs are suitable for wavelength-division-multiplexing (WDM) transceiver and integrated optoelectronics. They have been considered as the new solution for InP-based tunable photodetectors [4]. These photodetectors can also be regarded as efficient photodetectors for on-chip optical interconnection [3].

In conventional vertical RCEPDs the photon lifetime is very small and the optical demodulation bandwidth (ODB) is large, thus, its effect in sub-terahertz applications is neglected [1]. Therefore, in previous reports on bandwidth of RCEPDs, the effect of optical bandwidth has been ignored [4-6]. In RCE-WGPD the photon lifetime can be large enough, so its ODB must be considered in high speed design. In this paper, we present analytical models for bandwidth of RCE-WGPD and ODB of MRWPDs. Based on the models, we discuss the effects of some design parameters as effective absorption, effective radius, and coupling coefficient on the ODB of MRWPDs. A new silicon MRWPD is introduced and its high speed performance is analyzed. Due to integration and cost considerations, there is a long-time interest in long-wavelength silicon based photodetectors. Although some methods have been recognized for sensitizing of silicon beyond 1.1 μm wavelengths, these methods only provide low absorption coefficients and in the best cases, the long-wavelength silicon photodetectors have very large size_and low bandwidth-efficiency product (BEP). We predict, by utilizing known silicon absorption enhancement methods, the proposed silicon based MRWPD provide an efficient solution for high BEP, low volume, tunable, WDM long-wavelength photodetector.

2. BANDWIDTH OF MICRORING PHOTODETECTORS

2.1 Efficiency 3dB Bandwidth

The bandwidth of an optically wideband photodetector has modeled as $f_{3dB}^{-2} = f_{RC}^{-2} + f_{tr}^{-2}$, where f_{RC} and f_{tr} are the charging time limited and the carrier transit time limited 3dB frequencies, respectively[7]. In the optically narrow-band photodetectors we extend the above model as

$$\frac{1}{f_{3dB}^2} = \frac{1}{f_{RC}^2} + \frac{1}{f_{tr}^2} + \frac{1}{f_{opt}^2} \tag{1}$$

where f_{opt} is the photon lifetime limited 3dB frequency and is determined from optical demodulation response of photodetector. This concept is in agreement with what is presented in [8] for electronics circuits.

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2.2 Optical Demodulation Bandwidth

The electric field of input optical AM signal can be expressed as

$$E_{in} = E_0 \cos(\omega_0 t) E_m \cos(\omega_m t) \tag{2}$$

where ω_0 and ω_m are frequency and E_0 and E_m are normalized amplitude of carrier and modulated signals, respectively. Using the optical model of microring photodetector proposed in [2] and supposing that ω_0 is a resonance frequency of MRWPD, we obtain the optical response as

$$P_{abs}(\omega_m) = \frac{(1-|t|^2)(1-e^{-2\Gamma\alpha L_r})}{1+|t|^2 e^{-2\Gamma\alpha L_r} - 2e^{-\Gamma\alpha L_r}|t|\cos(\frac{\omega_m n_r L_r}{c})}(E_0 E_m)^2 \tag{3}$$

here q, h and c are electron charge, Plank's constant and free-space light velocity and Γ, α, n_r, L_r and t are confinement factor, field attenuation coefficient, effective refractive index, resonator length and transmission coefficient of coupler section, respectively. Now, one can extract the ODB of MRWPD, f_{opt}, as

$$f_{opt} = \frac{c}{2\pi n_r L_r}\cos^{-1}\left(1-\frac{(1-|t|e^{-\Gamma\alpha L_r})^2}{2|t|e^{-\Gamma\alpha L_r}}\right) \tag{4}$$

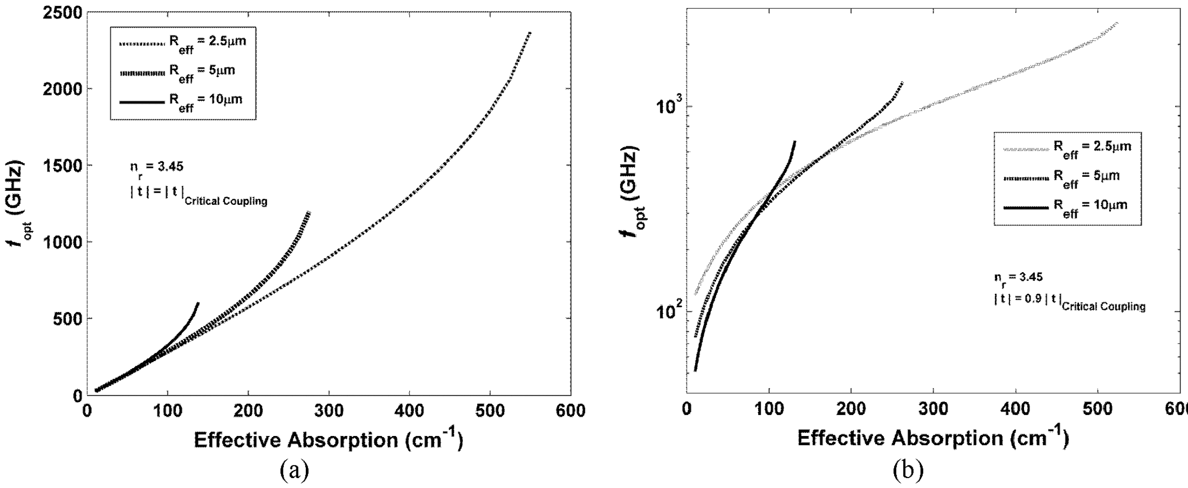

Figure. 1. ODB variation of MRWPD against effective absorption for several effective radiuses (a) critical coupling case, (b) overcoupled case.

Figure 1*a* shows ODB variation of MRWPD against effective absorption for several effective radiuses at critical coupling. In this condition and for low absorptive materials, the optical bandwidth linearly increases with effective absorption. We observe that the ODB for high Q cavity, i.e. low effective absorption, is very small and weakly depends on cavity length. On the other hand, for high absorption structures, ODB strongly depends on cavity length, and its maximum is mainly determined by effective radius. As the effective absorption increases, the photon lifetime decreases and optical bandwidth increases. These results denote that short cavity structures are ideal for very high speed photodetection. The small radius microrings allow the design of larger thickness absorption layer in MRWPDs. In Fig. 1*a*, ODB is not defined for some ranges of effective absorption and effective radius, because in these cases the interference behavior of coupled microring waveguide vanishes and the frequency selectivity disappears. Using (4), we obtain a general condition for *frequency selectivity margin* (FSM) as $|t|\exp(-\Gamma\alpha L_r) \geq 0.1716$. This imposes a limit on minimum value of |t| which equals 0.1716.

In MRWPD, the photon lifetime can be adjusted with both absorption and coupling parameters. Figure 1*b* shows ODB variation of MRWPD against effective absorption for several effective radiuses in overcoupled structure. In this case, the ODB for low absorption materials is larger relative to critical coupling condition. It should be noted that the increase of bandwidth is achieved with the decrease of device efficiency.

2.3 High Speed Photodetector Design

Here, we introduce the novel silicon MRWPDs [3] and investigate their high speed performance using bandwidth and BEP figure of merits. It is shown, with optimized design, these silicon photodetectors provide BEP in order of several tens gigahertz. Figure 2 schematically shows the structure of silicon-based MRWPD. It contains a lateral PIN photodiode in which the p$^+$-silicon region is placed inside the microring section.

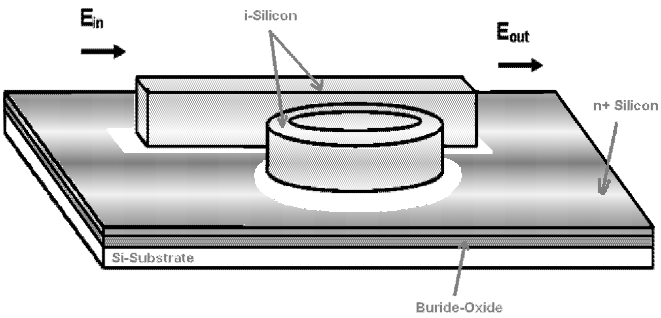

Figure 2. 3D schematic of the silicon-based MRWPD.

The variations of its three bandwidth components, f_{opt}, f_{RC} and f_{tr}, versus the width of absorption region at several wavelengths 0.850, 0.980 and 1.064 μm, are calculated and depicted in Fig. 3. The calculation is performed using silicon parameters given in [9-10]. The absorption of silicon near its band-edge is about several tens per centimeter. It shows, for λ = 0.980 μm and λ = 1.064μm the limiting factor of total bandwidth is f_{opt}. In these cases, to optimize the efficiency and BEP, one can design the optical structure at partially overcoupling condition.

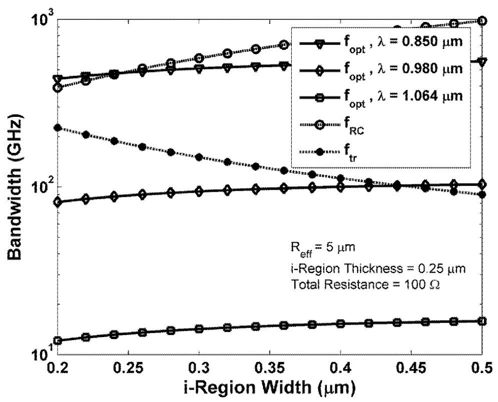

Figure 3. The variations of three bandwidth components, f_{opt}, f_{RC} and f_{tr}, versus the width of absorption region at several wavelengths 0.850, 0.980 and 1.064 μm.

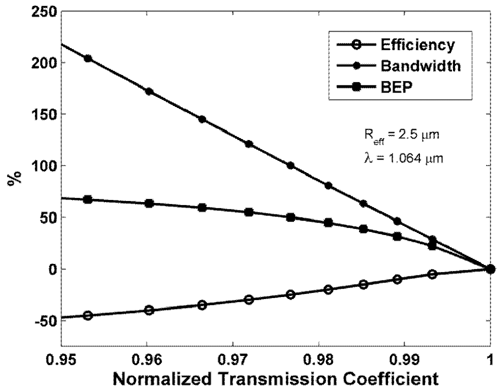

Figure 4. The relative variations of efficiency, bandwidth and BEP versus normalized transmission coefficient of MRWPD in partially overcoupling condition.

Figure 4 depicts the relative variations of efficiency, bandwidth and BEP versus transmission coefficient of MRWPD normalized to critical coupling transmission, t_c, in this condition. It shows, in device with R_{eff} = 2.5 μm, at λ = 1.064 μm, reduction of transmission coefficient from $t = t_c$ to $t = 0.975t_c$ results in 100% increment of bandwidth, 25% reduction of efficiency and 50% increment of BEP. Figure 5 shows the BEP as a function of i-region width for different wavelengths at critical coupling. We observe that BEP in order of several tens gigahertz is achieved even at very low absorption conditions for a low volume (about 2 μm^3) active region silicon photodetectors.

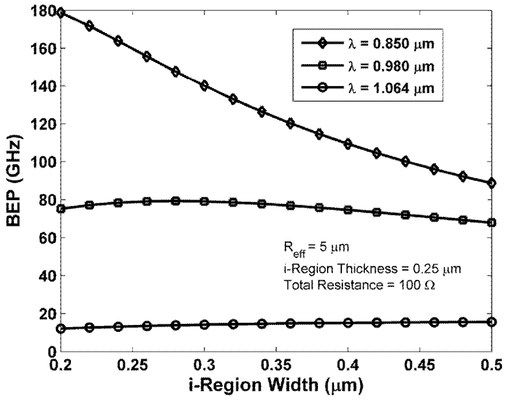

Figure 5. BEP of the silicon-based MRWPD in interested wavelengths.

3. DISCUSSION AND CONCLUSION

Considering the photon lifetime in resonant cavity, we have presented analytical model for bandwidth and BEP of MRWPDs. This model provides the criteria for design and evaluation of these photodetectors for high speed applications. It can be used for all kind of RCE-based photodetectors in situations that f_{opt} is comparable with f_{tr} or f_{RC}. At terahertz frequency applications this condition is valid for conventional RCEPDs [1]. In addition, the ODB of MRWPDs has been determined and discussed. It has been shown the low absorption and critical coupled microrings have low ODB. In these cases, the bandwidth of MRWPDs is limited by ODB. On the other hand, the short cavities and partially overcoupled structures are suitable for very high speed photodetectors. The small radius MRWPDs which are suitable for large-scale integration, have a wide free spectral range and can be utilized as integrated selective terahertz photodetectors. We have shown the novel silicon MRWPD can provide both high efficiency and large BEP even at very low absorption structure. This is an important feature of RCE-WGPDs. With some enhancement technology to increase the long-wavelength absorption of about 100 cm^{-1} in silicon-based structures, the proposed MRWPD provide the efficient solution for high BEP, low volume, tuneable, WDM long-wavelength silicon photodetectors both for telecommunication and optical interconnections in VLSI circuits.

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