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Two-photon absorption effect on semiconductor microring resonators

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ABSTRACT

We present an approach of counting high order nonlinear optical (NLO) effects on coupling efficiency, resonance wavelength, and optical bistability of semiconductor microring resonators. In our study, we include Kerr effect, two-photon absorption (TPA), free-carriers (FC), and loss. Unlike to previous studies, we included intensity-dependent coupling coefficients effects on resonance wavelength shift and optical bistability behavior, in addition to the other NLO effects. The results show light transmission between couplers decreases at high light intensities. Also, a blue shift is seen on resonance wavelength of microring in nonlinear regime. Optical bistability of microring is dramatically affected at high light intensity, too. Instability of microring operation due to NLO effects at very high light intensities is reported.

1. Introduction

Active coupled microresonators interactions have extensive applications in integrated photonic devices. To achieve functional integrated devices using microresonators, one needs to control coupling efficiencies, refractive index, and losses in microring resonators to achieve switches, modulators, and optical filters [1,2]. Also active microresonators employing semiconductor materials have been employed [3] in nonlinear regime. Such ring–waveguide interactions can be used to perform all-optical switches [4], optical transistor actions [5], optical bistable devices [6–9], and other signal processing functionalities [10].

Although, many researches on microring resonators are focused on nonlinear regime, but coupling coefficients are regarded as a constant and dependency of the coefficients to light intensity are neglected. As the operation of microrings basically depends on coupling process, in this paper coupling coefficients are studied with inclusion of Kerr effect, TPA, FC, and loss. In addition, we investigated intensity-dependent coupling coefficient effects, Kerr effect, TPA, FC, and loss effects on resonance shift and optical bistability of microring. Therefore, in the next section we examine the coupling of semiconductor-based microring resonators with taking into account Kerr effect, TPA, FC, and loss. In our approach, we use extended NLDC equations [11] in segmented parallel waveguides [12], [2]. Next, in Section 2 and 3, we investigate resonance shift and optical bistability of microrings, respectively, by using a numerical method and inclusion of high order NLO effects such as Kerr effect, TPA, FC, loss, and intensity-dependent coupling coefficient effects. Finally, the NLO effects on stability of microring's operation at very high light intensities will be discussed.

2. TPA effect on coupling efficiency

As optical microring resonators provide intensity buildup and enhance NLO effects such as TPA and FC, these phenomena cause additional nonlinear loss which degrades the resonator performance. In TPA process of semiconductor materials, an electron in the valence band is excited by two coincident photons in the conduction band and FC generated at steady state can be approximated as $\Delta N_c \cong \left(\alpha_2\tau_f/2\hbar\omega\right) I^2$ [13], where $\hbar\omega$ is the photon energy, I is the field intensity of light, τ_f is FC life time, and α_2 is TPA coefficient. The generation of FC due to TPA creates additional loss known as free-carrier absorption, and induces refractive index change proportional to squared light intensity. Therefore, the absorption coefficient and refractive index of the semiconductor will be given by

$$\alpha = \alpha_0 + \left(\alpha_2 + \alpha_{fc}I\right) I \quad (1)$$

$$n = n_0 + (n_2 - n_{fc}I)I \quad (2)$$

where α_0 and n_l are linear absorption coefficient and linear refractive index, respectively, n_2 is the second order index of refraction (Kerr coefficient), $\alpha_{fc} = \sigma_a\alpha_2\tau_f/2\hbar\omega$ is FC induced nonlinear absorption coefficient, and $n_{fc} = \sigma_r\alpha_2\tau_f/2\hbar\omega$ is FC induced nonlinear refractive index coefficient of the medium. σ_a is the free carrier absorption cross section and σ_r is the change in refractive index per unit conduction band electron density. Therefore, the extended

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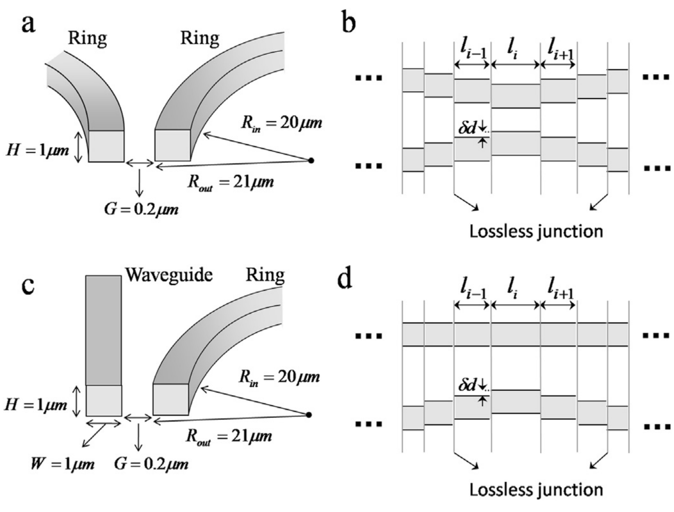

Fig. 1. Segmentation of coupling region for (a) lateral state of ring–ring coupler and its segmentation in (b), and for lateral state of ring–waveguide coupler in (c) and its segmentation in (d). In part (b) the parameter $\delta d = 0.01\ \mu m$ and in part (d) the parameter $\delta d = 0.005\ \mu m$.

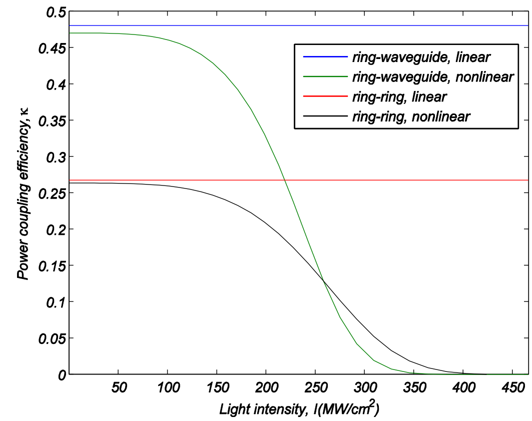

Fig. 2. Power coupling efficiency κ versus light intensity. Red and blue lines are related to linear coupling calculations without NLO effects for ring–ring and ring–waveguide arrangements, respectively. Black and green lines are related to nonlinear coupling of ring–ring and ring–waveguide arrangements, respectively, with inclusion of Kerr effect, TPA, FC, and loss. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nonlinear directional coupler equations include TPA, FC, and loss effects are [11]

$$-i\frac{dA_1(z)}{dz} = Q_1A_1(z) + Q_2A_2(z) + \left(Q_3\left|A_1(z)\right|^2 + 2Q_4\left|A_2(z)\right|^2\right)A_1(z)e^{-\alpha_0 z} - \left(Q_5\left|A_1(z)\right|^4 + 6Q_6\left|A_1(z)\right|^2\left|A_2(z)\right|^2\right)A_1(z)e^{-2\alpha_0 z} \quad (3\text{-a})$$

$$-i\frac{dA_2(z)}{dz} = Q_1A_2(z) + Q_2A_1(z) + \left(Q_3\left|A_2(z)\right|^2 + 2Q_4\left|A_1(z)\right|^2\right)A_2(z)e^{-\alpha_0 z} - \left(Q_5\left|A_2(z)\right|^4 + 6Q_6\left|A_2(z)\right|^2\left|A_1(z)\right|^2\right)A_2(z)e^{-2\alpha_0 z} \quad (3\text{-b})$$

where $A_1(z)$ and $A_2(z)$ are the wave envelop functions, Q_1 and Q_2 are overlap integrals of linear coupling coefficients, Q_3 and Q_4 are intensity-dependent nonlinear coupling coefficients resulted from Kerr effect, and Q_5 and Q_6 are intensity-dependent nonlinear coupling coefficients resulted from TPA and FC.

Power transfer between two optical modes occurs when there is a significant field overlap between the modes. Similarly, transmission power between microrings occurs in places where the bodies of microrings are in closed proximity as shown in Fig. 1. In the case of the lateral coupling of two ring resonators or ring and waveguide, the spacing between waveguides in coupling region varies along the propagation direction gradually, and the coupler is usually designed to keep the radiation very small. Thus, the coupler can be divided into segmented stages, and the propagation characteristics of the whole coupler can be obtained by cascading the partitioned waveguides and solving extended NLDC Eq. (3) for each stage, separately [12]. Here, we apply the same analogy used in Refs. [14] and [12] for calculating lateral coupling of microring–waveguide and microring–microring arrangements.

Fig. 2 shows the power coupling efficiency κ versus incident light intensity. The coupling efficiency κ is defined as the ratio of exchanged light intensity between microrings (or waveguide and microring) to its incident intensity. The red and blue lines are related to linear coupling calculations without NLO effects for ring–ring and ring–waveguide, respectively. The black and green lines are related to nonlinear coupling with inclusion of Kerr effect, TPA, FC, and loss for ring–ring and ring–waveguide arrangements, respectively. The refractive index of the core and clad of GaAs-based microring and waveguide are 3.47 and 3.25, respectively. The Kerr coefficient is $n_2 = 3.3 \times 10^{-13}\ cm^2\ W^{-1}$ and FC induced nonlinear refractive index coefficient is $n_{fc} = 7.45 \times 10^{-21}\ cm^4\ W^{-2}$.

The electric field distribution $E^x_{1,1}$ mode with propagation constant $\beta = 1.33158 \times 10^7\ m^{-1}$ at telecommunication wavelength $\lambda = 1.55\ \mu m$ is used for counting the overlap integrals $Q_1 - Q_6$. As shown in Fig. 2, in the interval of input light intensity $0 - 50\ MW/cm^2$ all of the power coupling efficiencies are constant but, by increasing the input intensity from $50\ MW/cm^2$ up to $150\ MW/cm^2$, the nonlinear power coupling efficiencies decrease gradually. In the interval of $150 - 300\ MW/cm^2$ the nonlinear power coupling efficiencies decrease very fast and finally, those vanish approximately at threshold light intensity at about $400\ MW/cm^2$. The threshold light intensity is defined as the value of incident light intensity in which there is no significant light exchange between the couplers. Also, at low light intensities in the interval of $0 - 50\ MW/cm^2$ there is a little bit difference between the values of linear and nonlinear power coupling efficiencies for example, between the red and black lines or between the blue and green lines. These small differences are due to loss effects and light attenuation in the coupling region in the nonlinear calculations. Although in interval of $0 - 50\ MW/cm^2$ we have linear behavior in the black and green lines, but linear loss effects cause such difference between the linear and nonlinear coupling efficiencies. Also, because of the length of the coupling region in the ring–waveguide arrangement is longer than the ring–ring arrangement (it can be understood from part b and d of Fig. 1), light attenuation related to coupling region of ring–waveguide coupler is more than that of in the ring–ring coupler. Therefore, the difference between the value of blue and green lines is a little bit more than the difference between the values of the red and black lines in the interval of $0 - 50\ MW/cm^2$.

The decrease of power coupling efficiencies arises from refractive index variation induced by NLO effects in the couplers. The light transfer between microrings is limited by nonlinear variation of refractive index, and so it is drastically depends on the light intensity in nonlinear regime. The reason can be better comprehended by mismatching concept in waveguide's coupling. When the incoming light intensity increases to high value, the phase of light will be modified by itself in Self-Phase Modulation (SPM) and the light of adjacent core in Cross-Phase Modulation (XPM) process. These NLO effects induce refractive index variation and thus, the mismatch parameter increases and this effect reduce the rate of exchange of light between the couplers. This phenomenon is useful to control and modify light transfer and coupling efficiencies. This