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Investigation on a microring laser coupled with phase-section bus waveguide as a tunable transmitter for application in future optical/wireless hybrid networks

S. Mikroulis [a,b,*], S. Karabetsos [a], E. Pikasis [a,b], A. Nassiopoulos [a],
A. Bogris [b], D. Syvridis [b]

[a] *Technological Educational Institution (TEI) of Athens, Electronics Department, RDTL Laboratory, Greece*
[b] *University of Athens, Department of Informatics and Telecommunications, Optical Communication Group, Greece*

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Abstract

In this paper, semiconductor microring lasers with integrated phase sections in the bus waveguide are numerically evaluated, using a dynamic multimode laser model, and investigated as low-cost, integrated, potential tunable directly modulated transmitters for future hybrid optical–wireless networks. The effect of optical feedback through bus waveguide is revealed as a promising mechanism for improving nonlinear distortion. Additionally, tunability is achieved with the aid of phase-tuning. The underlying laser dynamics beyond this behavior are analyzed.

Keywords: Microring laser; Optical feedback; Nonlinear distortion; Radio over fiber

1. Introduction

Semiconductor microring lasers are promising candidates in order to play the role of low-cost optical transmitters thanks to their ultra-compactness, which can lead to dense monolithic integration, and improved spectral purity. Moreover, the combination of active/passive devices can lead to a variety of all-optical logic bit-level functions on the same chip. Recently, fabricated microring lasers were directly modulated up to 7 Gb/s recording adequate performance in back to back transmission [1]. Moreover, numerical calculations using a multimode laser model at 10 Gb/s including single mode fiber (SMF) transmission over 10 and 20 km indicate the ability of successful performance at higher bit rates, with the aid of bus waveguide optical feedback [2,3]. In this way, multiwavelength operation through phase tuned bus waveguide can be feasible, enabling wavelength division multiplexing (WDM) operation.

Furthermore, moving towards high capacity next generation (i.e., 4G) wireless/cellular networks employing advanced and complicated signaling techniques, as well as utilizing higher frequency bands to cover the need for increased bandwidth, optical wireless convergence is sought, so as to exploit the optical channel capacity. In a dense wireless/cellular network, enhanced coverage as well as frequency reuse entails a smaller cell, requiring an

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* Corresponding author at: University of Athens, Department of Informatics and Telecommunications, Optical Communication Group, Greece.
E-mail address: spirosm@di.uoa.gr (S. Mikroulis).

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increased number of installed base stations (BS) to cover the same real estate. In order to minimize network installation and maintenance cost, it is desirable to simplify BSs by transferring many of the complicated and relative expensive signal processing (e.g., modulation, demodulation, synchronization, multiplexing, etc.) to the central station (CS). Such a case can be satisfied through the use of Radio over Fiber (RoF) technology, which can also be deployed over current as well as future deployed backbone Passive Optical Network (PON). In RoF, the BSs are linked to the CS via an optical fiber, providing the interface between mobile terminals and the CS hence, transferring all the signal processing at the CS. The BS mainly performs electrical-to-optical and optical-to-electrical conversion together with amplification. In this manner, RoF technology can be utilized as the physical infrastructure for next generation wireless broadband communications. In such technologies, orthogonal frequency division multiplexing (OFDM) has been widely adopted as a modulation scheme, offering enhanced merits not only at the wireless, but also at the optical domain as well [4]. In the above scenario, integrated, low-cost, tunable, directly modulated optical devices will be required that could potentially operate as multiwavelength optical sources in future hybrid optical/wireless networks [3,5].

In this manuscript, microring lasers with integrated phase sections in the bus waveguide (Fig. 1) are numerically evaluated, using a dynamic multimode laser model, and investigated as low-cost potential tunable directly modulated transmitters for RoF systems. Evaluation is performed by employing multiband-OFDM (MB-OFDM), a demanding signaling scheme in terms of transmission requirements, affected by the inherent non-linear nature of optical sources. More details on MB-OFDM can be found in section 2 and in [5]. Moreover, the effect of phase-shifted optical feedback through bus waveguide's facet residual reflectivity is explored as a promising mechanism for the suppression of the laser's inherent nonlinearity. In addition to this, the phase-shifted optical feedback, provided through integrated phase sections, is exploited for tunable functionality, enabling the appropriate multiwavelength operation needed by a proper transmission scheme. In this application context, apart from the technological importance of such a device, an additional aim of this work is to provide a physical insight on the complex behavior of such a multidimensional system, so the laser dynamics are analytically assessed, with the aid of the rate equation model [1,3]. Overall system evaluation is performed using standard qualitatively as well as quantitatively telecommunication figure of merits (see section 3), calculated when the modulation ratio is properly adjusted for all values of the laser's peak wavelength, which is further optimized at high values of bus waveguide reflectivity.

The rest of the paper is organized as follows. Section 2 discusses the system setup, while section 3 provides numerical results on different aspects of the system evaluation. Concluding remarks are given in section 4.

2. Theory and model

The system setup considered in the numerical calculations is presented in Fig. 2. Each subsystem is separately modelled, providing the necessary signal processing as well as the appropriate inputs to its next module. For the transmitter's (microring laser) accurate simulations, multimode rate equations are used [2,3]:

$$\frac{dE_{p,\pm m}}{dt} = \tfrac{1}{2}(1 + j\alpha)\left[G_{p,\pm m} - \frac{1}{\tau_p}\right]E_{p,\pm m} + \frac{K_{\mp m}}{\tau_{\mathrm{L}}}E_{p,\mp m}(t - \tau_{\mathrm{d}})\mathrm{e}^{-\mathrm{j}\omega_p\tau_d + \Delta\phi} + F_p(t), \tag{1}$$

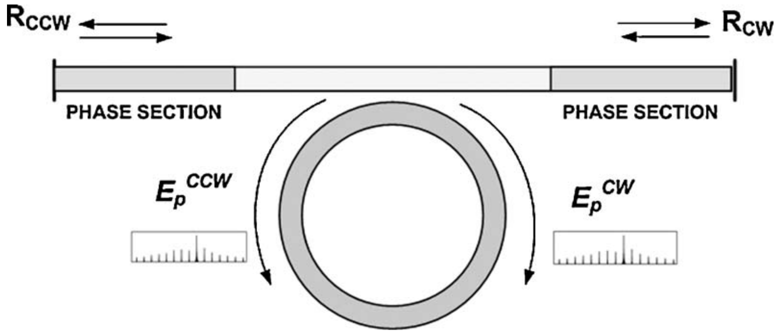

Fig. 1. Planar view of a semiconductor microring laser with added phase sections.

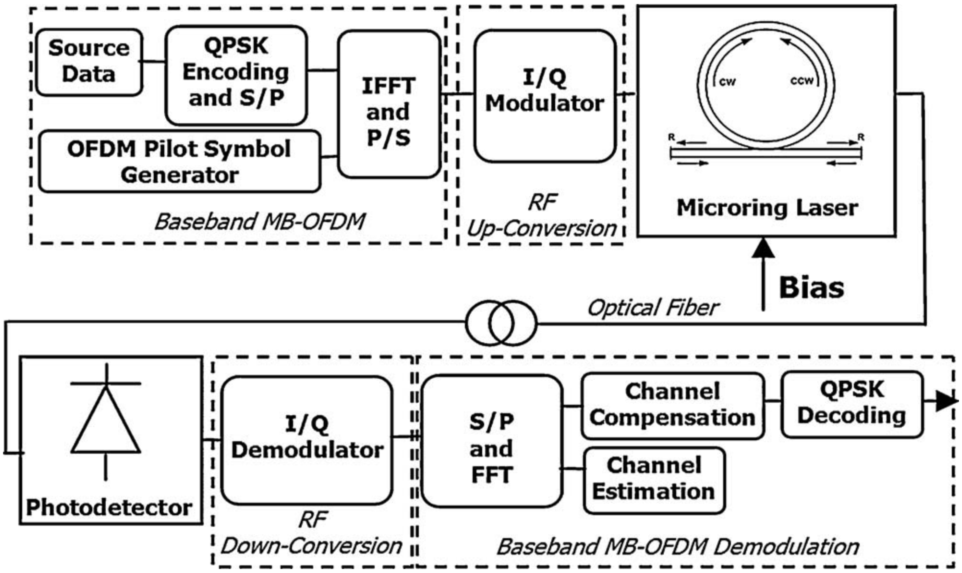

Fig. 2. Block diagram of the system model.

$$G_{p,\pm m} = A_p - sg(n-n_0)\left|E_{p,\pm m}\right|^2 - \sum_{p,q,\pm m} D_{p(q)}\left|E_{q,\pm m}\right|^2 - \sum_{p\neq q,\pm m} H_{p(q)}\left|E_{q,\pm m}\right|^2, \tag{2}$$

$$\frac{dn}{dt} = \frac{I}{eV} - \frac{n}{\tau_s} - \sum G_{p,\pm m}\left|E_{p,\pm m}\right|^2, \theta \tag{3}$$

where G_p is the modal gain, A_p the linear gain coefficient, s is the self gain suppression coefficient, $D_{p(q)}$, $H_{p(q)}$ are the symmetric and asymmetric cross gain suppression coefficients, and $\tau_L = Ln_g/c$, where $L = 2\pi R$. The laser's parameters for the numerical simulations can be found in previous studies [2,3]. The value of the bus waveguide reflectivity for both bus waveguide facets, R_f, is varied from 0.05 to 0.5, equivalent to power reflectivity values $R_{CW/CCW}$ from −26 to −6 dB in order to study the effect of the strength of the optical feedback in the microring laser's frequency response and nonlinearity. In each case, the bus waveguide length, L_b, has been assumed to be eight times the radii length, $L_b = 400$ μm. The delay time of the feedback power is then calculated as, $\tau_d = L_b n_g / c = 4.7$ ps. In the calculations below, we define the modulation ratio m_r as I_{mod}/I_b, where I_{mod} is the peak (max) OFDM modulation current, and I_b is the bias current. For all simulated cases, the laser's bias current is kept constant at $I_b = 2.0I_{th}$, whereas I_{mod} is varied and its influence on the MB-OFDM transmission is evaluated. In addition, a single mode optical fiber (SMF) in the order of 5 km is assumed and supposed to be ideal, while the photodetector is simulated using an additive Gaussian noise source.

MB-OFDM is currently the most widely deployed modulation scheme in ultra wideband (UWB) communication technology, developed primarily for wireless personal area networks (WPANs), operating at the 3.1–10.6 GHz frequency range [5]. In MB-OFDM the spectrum is divided into 5 band groups, each of them having 3 subbands, except of group 5, which has 2 subbands. Every subband occupies a bandwidth of 528 MHz. There is a total of 14 subbands, namely 1–14. Each MB-OFDM subband employs 122 quadratic phase shift keying (QPSK)-modulated subcarriers using a 128 fast Fourier transform (FFT) size. The subcarrier spacing is 4.125 MHz. In the developed model, prior to data transmission, a pilot OFDM symbol known to the receiver is sent, acting as a reference for correct demodulation through channel estimation.

3. Results and discussion

3.1. Effect of laser's intrinsic nonlinearity

One of the most critical issues in an optical transmitter which will be used in a RoF (i.e. analogue) system is the linearity of its light–current (P–I) characteristic. However the intrinsic nonlinear interaction between carriers and photons, due the photon–electron (P–E) resonance drastically increases the harmonic or intermodulation distortion especially as the modulation frequency approaches the laser's resonance frequency.

In order to qualitatively estimate the effect of the microring laser's nonlinearity, which is enhanced around the resonance frequency range, in MB-OFDM signal transmission along the UWB band, Fig. 3(a)–(c) depict calculated electrical spectra considering the following cases. The first case, shown in Fig. 3(a), illustrates the directly modulated microring laser on subband 1 (3.4 GHz) for $m_r = 0.25$ and $m_r = 0.47$ respectively. The laser's inherent nonlinearity results in both harmonic (HD) and intermodulation (IMD) distortion, leading to interband and intraband cross-talk effects. Indeed, from Fig. 3(a), harmonic distortion is observed at the frequency bands in the range of 6.8 GHz and 10.2 GHz, coinciding with MB-OFDM subbands 7 and 14. However, it is observed that harmonic components are suppressed by approximately more than 30 dB and 22 dB for $m_r = 0.25$ and $m_r = 0.47$ respectively. Moreover, Fig. 3(b) depicts the case where both subbands 1 (3.4 GHz) and 7 (6.6 GHz) are simultaneously transmitted. In this case, intermodulation products result in increased distortion in subband 13 (~9.8 GHz) which is more apparent for $m_r = 0.47$ where a suppression of less than 22 dB is observed. Fig. 3(c) shows the case of calculated spectrum simultaneously utilizing 3 MB-OFDM subbands, namely 1, 7 and 13. It is observed that nonlinear effects become more evident at higher frequency bands, near the resonance frequency, and increased modulation ratio as well. Indeed, spectrum spreading is almost negligible for $m_r = 0.25$, but this is not the case for $m_r = 0.47$. Intraband distortion cannot be easily observed through the spectrum graphs, since intermodulation products fall within utilized subbands.

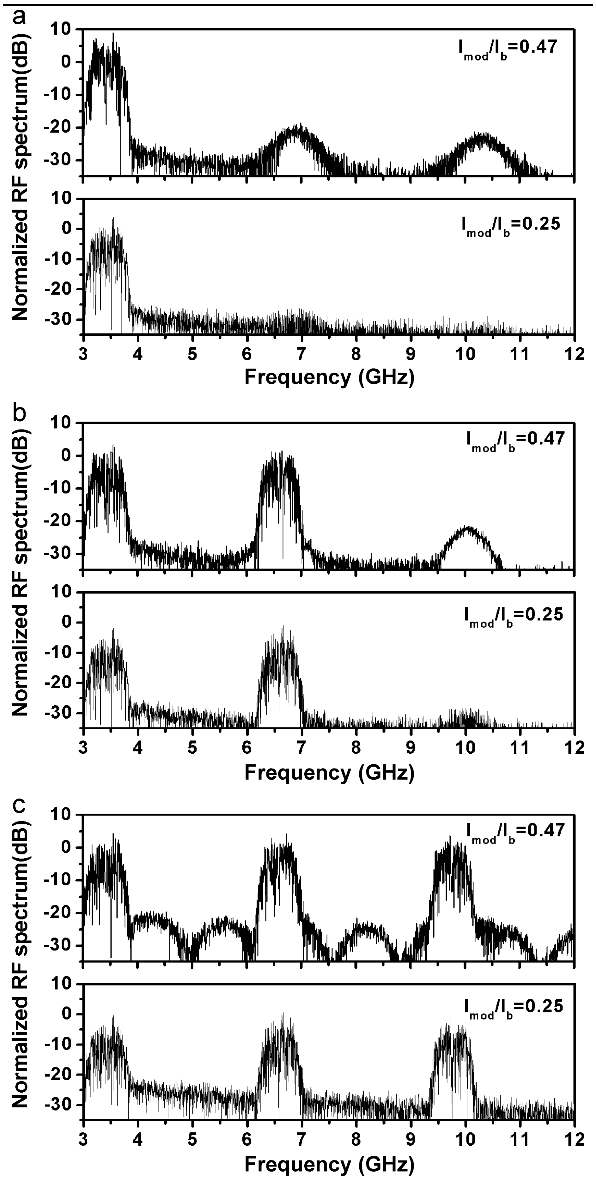

Fig. 3. Electrical spectra for: a) sub-band 1, b) sub-bands 1 and 7, and c) sub-bands 1, 7 and 13. In all cases, a modulation ratio of $m_r = 0.25$ and 0.47, respectively is considered.

In order to quantitatively evaluate the above considerations, error vector magnitude (EVM) is utilized as a figure of merit. The EVM is calculated as [5],

$$\mathrm{EVM} = \sqrt{\frac{\sum_N |r_n - s_n|^2}{\sum_N |s_n|^2}} \tag{4}$$

where r_n and s_n are the received and ideal constellation points respectively, and N is the number of constellation points. The EVM offers a quantitative evaluation for the spreading of the received constellation points.

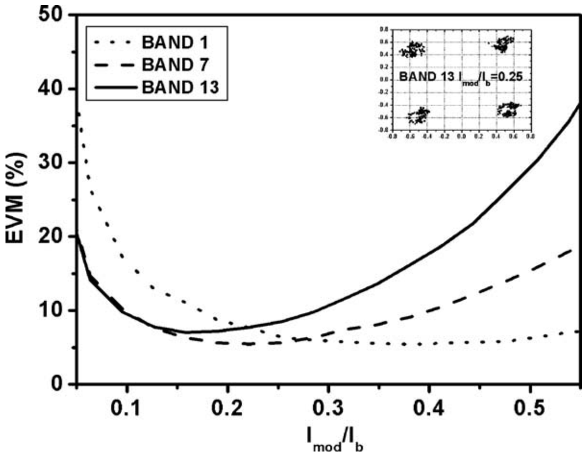

Fig. 4. EVM calculations for different MB-OFDM subbands.

Fig. 4 shows EVM calculations as a function of m_r for the MB-OFDM subbands 1, 7 and 13. In addition to this a respective constellation diagram is demonstrated for band 13 at a modulation ratio in the order of 0.25. It is depicted that for relatively low modulation ratios (i.e., $m_r < 0.15$) the EVM is increased, due to decreased signal to noise ratio (SNR). Moreover, for relatively increased modulation ratio (i.e., $m_r > 0.27$), EVM is increased due to increased nonlinear distortion due to the band frequency approaching the laser's resonance frequency. An optimum range in the order of 6% is achieved for a modulation ratio in the order of 0.2.

3.2. *Effect of phase-shifted coherent optical feedback*

A parameter that is of great importance in laser dynamics subject to coherent optical feedback (delayed equations) is the phase and strength of the backreflected field. In a previous study feedback power through bus waveguide reflectivity has been proved to promote the damping of the relaxation oscillations thus decreasing the transient chirp and eventually improving the chirp-limited performance [2] in a typical optical transmission scheme including SMF. In addition to the above effect, feedback power locks the microring laser ensuring single longitudinal mode operation, as in the general case ring laser is a multimode laser, combined with controlled oscillation direction diminishing thus the respective mode-hopping noise. In the microring laser case the effect of the feedback power is more complicated, with respect to a typical optical feedback scheme (i.e. distributed feedback (DFB) laser with external cavity configuration) due to the fact that the feedback power is re-injected in the opposite propagation direction. Apart from single mode operation the spectrally wide re-injected power in some manner acts as a holding beam, which stabilizes the unwanted transients in the carrier concentration acting mainly on the damping of relaxation oscillations. For the specific amount of the bus waveguide reflectivity and delay time considered in the context of this work, the dominant mechanism, controlling the high frequency response, is the damping of relaxation oscillations due to increased power inside the ring cavity. In this work, the values of feedback level (i.e. bus waveguide reflectivity) and phase are varied whilst the bus waveguide length is remained unchanged at eight times the ring radii, $R = 50$ μm ($L_b = 400$ μm). The equivalent delay time for the above bus waveguide length is 4.7 ps. As it has already been discussed in a previous work [2] the modulation performance is unaffected for an increment of the bus waveguide length up in the order of $L_b = 800$ μm (i.e. 16 times the ring radii), for a bus waveguide reflectivity $R_f = 0.1$, where a significant suppression of the optimum modulation performance is observed. The equivalent delay time for $L_b = 800$ μm is 9.4 ps. The same situation exists for other values of reflectivity i.e. $R_f = 0.3$, 0.5. This behavior can be attributed in the usual dynamic dependence on the delay time (hence bus waveguide length) of systems that are described with delay equations where at large time delays an unstable (coherence collapse) regime should be observed.

In the context of this work, optical feedback is also used for achieving tunable functionality through the alteration of field's optical phase and in a second stage for a significant decrease of the nonlinear distortion through the suppression of the P–E resonance (and respective relaxation oscillations). An alteration of the field's optical phase is realized with the inclusion on the device's design phase sections which can be integrated in the bus waveguide [6] enabling wavelength tuning (i.e. WDM operation). The numerical simulations revealed that phase-shifted feedback apart from promoting single-mode operation can either tune the laser at a different wavelength. It is calculated that phase alteration ($\Delta\varphi = \pi/2$, $\Delta\varphi = 0$, $\Delta\varphi = 2\pi/3$) shifts the laser's peak wavelength between adjacent modes; $\lambda_0 = 1550$ nm, $\lambda_1 = 1552.2$ nm and $\lambda_3 = 1554.4$ nm. A similar wavelength tuning behavior has been also experimentally demonstrated in microring lasers with larger ring radii [7], using active bus waveguide configuration. EVM calculations have been used in order to study the effect of phase tuning in the MB-OFDM performance, as it is discussed above. Fig. 5 shows calculated EVM values for the 3rd MB-OFDM band (13) for a peak wavelength of $\lambda_0 = 1550$ nm,

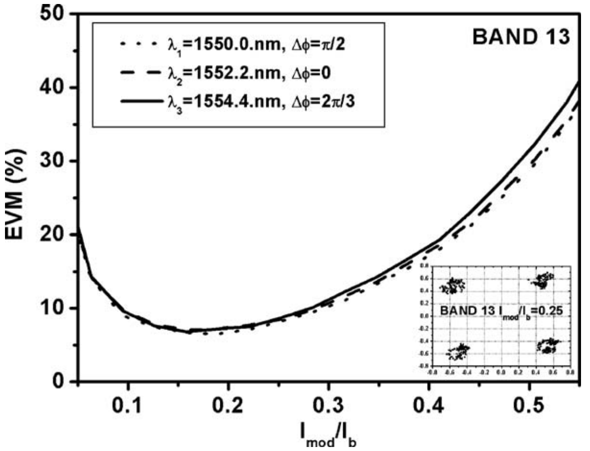

Fig. 5. EVM calculations for different values of the laser's peak wavelength, with the aid of phase tuning.

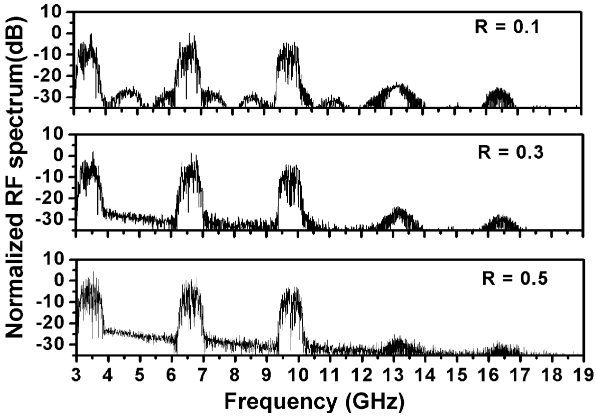

Fig. 6. Electrical spectra for different values of bus waveguide reflectivity $R = R_f = 0.1$, 0.3, 0.5 for sub-bands 1, 7 and 13. In all cases, a modulation ratio of $m_r = 0.47$ is considered.

$\lambda_1 = 1552.2$ nm and $\lambda_3 = 1554.4$ nm, respectively, at different values of phase (i.e. $\Delta\varphi = \pi/2$, $\Delta\varphi = 0$, $\Delta\varphi = 2\pi/3$). In addition to this a respective constellation diagram is demonstrated for band 13 at a modulation ratio in the order of 0.25. An optimum EVM performance in the order of 6% is depicted when the modulation ratio is properly adjusted for all values of the laser's peak wavelength.

As it has already been discussed, optical feedback through residual bus waveguide reflectivity can suppress the relaxation oscillations owing to the P–E resonance frequency. A significant damping of the resonance frequency has been numerically calculated in a previous work [2]. In the present work, the above mechanism is proposed for a substantial reduction in the nonlinear distortion, due to the P–E resonance, of the microring laser when it is used in a RoF system.

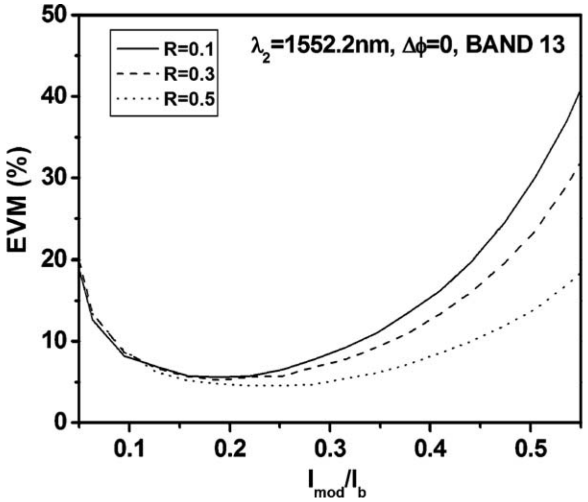

Fig. 7. EVM calculations for different values of the bus waveguide reflectivity, $R = R_f = 0.1$, 0.3 and 0.5 for subband 13.

As it has previously been discussed, a qualitative estimation on the microring laser's nonlinearity, which is enhanced around the resonance frequency range, can be extracted with the aid of electrical spectra. Different electrical spectra corresponding to values of bus waveguide reflectivity $R_f = 0.1$, 0.3, 0.5 for subbands 1, 7 and 13 are depicted in Fig. 6. As it is illustrated, the increased optical feedback through residual reflectivity significantly reduces both harmonic and intermodulation products. Moreover, EVM calculations at subband 13 (Fig. 7) demonstrate a significant reduction of respective values at high modulation ratios, in accordance with the laser's nonlinearity reduction due to the suppression of the microring laser's resonance frequency.

4. Conclusions

In this work, microring lasers with integrated phase sections in the bus waveguide are numerically evaluated, using a dynamic multimode laser model, and investigated as low-cost potential tunable directly modulated transmitters for future hybrid optical–wireless networks. The effect of phase-shifted optical feedback through bus waveguide reflectivity is proposed as a hopeful mechanism for improvement the laser's performance, in terms of tunability and nonlinear distortion reduction, and the underlying laser dynamics are analyzed.

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