Harmonic Distortion in Slow Light SOA based Microwave Photonic Phase Shifters

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Abstract: We present a theoretical and experimental evaluation of any general order harmonic distortion in a SFL phase shifter based on CPO in a SOA and propose different optical filtering implementations for distortion-free design.

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1. Introduction

Slow and Fast Light propagation (SFL) [1], is currently attracting a considerable interest in the field of microwave photonics as it offers the potential application to the implementation of tunable broadband RF phase shifters. One of the most promising optical phenomena that allows the control of the optical signal group velocity is that based on the coherent population oscillations (CPO) in semiconductor optical amplifiers (SOAs) [2], where a tunable microwave phase shift can be achieved by controlling the operation conditions of the SOA followed by a selective sideband filtering enhancing scheme. However, as an inherent nonlinear process, CPO can also bring the generation of harmonic distortion within the SOA which implies a reduction in the expected microwave phase shift [3].

We present a model based on the optical field that accounts for any general order harmonic distortion in a SFL phase shifter based on CPO in a SOA device. The model has been tested against the experimental results obtained for second order harmonics showing an excellent agreement. For microwave photonic applications where large signal operation is required, we propose two different optical filtering implementations for the proper design of distortion-free microwave photonic phase shifters.

2. Theoretical Model

We assume an input field to the SOA device given by the output of a dual-drive electrooptic modulator (EOM). Since many microwave photonic applications require operation at large modulation indices, we consider the harmonic distortion already introduced by the EOM, instead of assuming an ideal device, [3]. Although the model can be generalized for any value of chirp in the EOM, we consider the case for zero-chirp since the experimental validation is carried under such condition. The absence of the modulator chirp is produced by applying an electrical voltage on both electrodes such that $V_1(t)$=-$V_2(t)$. Assuming a voltage signal applied to the first electrode composed of a bias term V_{DC_1} and an RF signal whose amplitude, frequency and initial phase are V_{RF}, Ω and Φ_1 respectively,

$$V_1(t) = V_{DC_1} + V_{RF}\cos(\Omega t + \phi_1), \tag{1}$$

the optical field at the modulator output can be written in terms of Bessel functions of the first kind

$$E_{out}(t)\big|_{EOM} = \frac{E_S}{2}\cos(\varphi_1)J_0(m) + E_S\sum_{n=1}^{\infty}(-1)^n\left\{J_{2n}(m)\cos(\varphi_1)\cos\left[2n(\Omega t+\phi_1)\right] + J_{2n-1}(m)\sin(\varphi_1)\cos\left[(2n-1)(\Omega t+\phi_1)\right]\right\} \tag{2}$$

where E_s represents the input intensity provided by the laser, φ_1 the normalized (to the quadrature voltage V_π) bias voltage applied to the first electrode, $\varphi_1 = V_{DC_1}\pi / V_\pi$, and the modulation index is defined as $m = V_{RF}\pi / V_\pi$.

If we consider harmonic distortion up to order M, the field inside the cavity of the SOA can be expressed as:

$$E(t,z) = \sum_{k=-M}^{M} E_k e^{-j\left[(\omega_0+k\Omega)t-\beta_k z\right]} \tag{3}$$

where ω_0 is the frequency of the optical carrier, Ω is the modulation frequency and β_k is the propagation constant of the field complex amplitude E_k, the initial value of which is obtained from (2). Assuming perfect phase matching between the different RF terms, we can express the intensity of the intra-cavity field as a periodic function

$$\left|E(t,z)\right|^2 = \sum_{m=-2M}^{2M} S_m e^{-jm\Omega t} \tag{4}$$

being:

$$S_m = \sum_{k=-M+m}^{M} E_k E^*_{k-m}. \tag{5}$$

We can therefore assume that the carrier density inside the SOA, and thus the gain coefficient, oscillates following a similar variation of (4), which can be obtained from the well know carrier rate equation:

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_s} - \Gamma a\left(N - N_{tr}\right)\left|E\right|^2 \qquad (6)$$

being I the injection current, e the unit electron charge, V the volume of the active region, τ_s the carrier lifetime, Γ the confinement factor, a the differential gain and N_{tr} the transparency carrier density. The identification of every frequency population component in (6) yields the coefficients for the dynamic evolution of the gain:

$$g(t) = \sum_{m=-2M}^{2M} g_m e^{-jm\Omega t}. \qquad (7)$$

For the DC component we get $g_0 = \Gamma\bar{g}/(1 + S_0 / P_{sat})$, where $\Gamma\bar{g}$ is the unsaturated modal gain and the saturation power is defined as $P_{sat} = 1/(\Gamma a \tau_s)$; while for the rest of oscillating terms we have

$$g_m = -g_0 \frac{S_m / P_{sat}}{1 + S_0 / P_{sat} - jm\Omega\tau_s}. \qquad (8)$$

Substituting (1) and (7) in the slowly varying propagation equation, we get the coupled differential equations

$$\frac{dE_k}{dz} = -\frac{1}{2}\gamma_{\text{int}} E_k + \frac{(1 - j\alpha)}{2}\sum_{m=-M+k}^{m=-M+k} g_m E_{k-m}, \qquad (9)$$

where γ_{int} corresponds to the internal waveguide losses and α to the SOA linewidth enhancement factor. It must be noted that this model generalizes the results of [3].

3. Harmonic Distortion Evaluation

When optical filtering is included to selectively suppress the red-shifted frequency sideband of the optical signal before photodetection [3-5], the refractive index dynamics leads to a considerable increase in the microwave phase shift. However, the impact of harmonic distortion over the phase shifter performance is less well understood. To validate the results of the developed model and subsequently apply it to understand the effect of harmonic distortion, we have assembled the experimental setup shown in Fig. 1. A CW laser at 1550 nm is modulated by a 20 GHz microwave tone by means of a dual-drive zero-chirp EOM. The SOA has a bandwidth over 50 GHz and its bias has been set to 200 mA. Other parameters used in the SOA model are: linewidth enhancement factor α=2.4; length L=1 mm; unsaturable loss (1/m) γ_{int}=4/L; unsaturated modal gain (1/m) $\Gamma\bar{g}$ =5.5/L. Harmonic levels and phase shifts were measured using a Lightwave Spectrum Analyzer (LSA) and a Vector Network Analyzer (VNA) respectively.

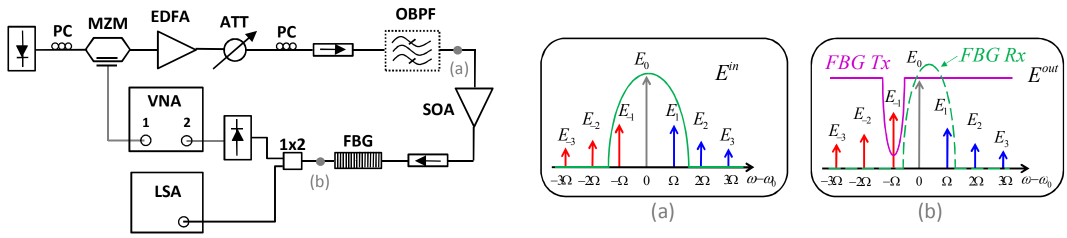
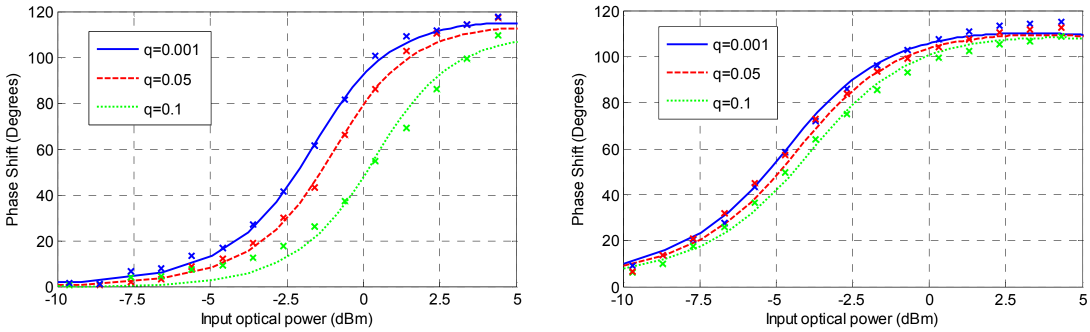


Fig. 1. Schematic of the general experimental setup. (a) Optical filtering for harmonic distortion reduction before SOA propagation. (b) Both FBG transmission and reflection schemes for optical post filtering.

The typical filtering configuration after the SOA is a notch filter implemented by a Fiber Bragg Grating in transmission (FBG Tx), as shown in the inset (b) of Fig. 1. In our experimental setup we employed a device providing around a 40 dB attenuation level. Fig. 2 (a) shows the experimental and theoretically obtained microwave phase shift for the fundamental tone for this notch filtering case and different modulation depths $q = |E_1(0)|^2 / |E_0(0)|^2$. A considerable dependence of the phase shift with q is observed, as expected, since for higher modulation depths there is a nonnegligible interaction between the fundamental tone and the harmonics within the SOA device, leading to power and phase fluctuations. Note that the experimental and theoretical results show an excellent agreement, validating the model developed in section 2. To overcome the dependence of the phase shifter performance on q, we propose a prefiltering scheme whereby a FBG passband filter is used previous to the SOA, to attenuate (more than 20 dB) the high-order harmonics produced by the EOM. Fig. 2 (b) shows the corresponding theoretical and experimental values of the phase shift. On one hand, we appreciate that the phase shift performance is considerably more independent on q, i.e. harmonic distortion is significantly reduced since there is no substantial energy leak/phase change in the fundamental tone. Secondly, if compared to the results of Fig. 2 (a), we can see that less optical power is required to achieve a given phase-shift value. The former scheme has the drawback of requiring pre and post filtering stages. A second alternative to reduce harmonic distortion consists in using a single bandpass post filtering stage shown in inset (b) of Fig. 1, implemented by a FBG now operating in reflection, yielding over 30 dB



(a) (b)

Fig. 2. Theoretical (lines) and experimental (markers) RF phase shift for (a) post filtering with an FBG operating in transmissium and (b) simultaneous pre and posfiltering schemes.

attenuation both for the red-shifted sideband and the remaining higher order frequency components. Fig. 3 illustrates the measured and computed results of the photodetected fundamental RF power, P(Ω), and the second harmonic power, P(2Ω), versus the SOA input optical power, for q=0.001. A very good level of agreement can be observed between the theoretical results and those rendered by the measurements. Comparing the second harmonic curve, it is appreciated how the inclusion of the optical notch filter (FBG Tx) results in a considerable increase of the nonlinear distortion level introduced by the CPO effect; which can be significantly decreased (by more than 10 dB) when resorting to the FBG in reflection (FBG Rx). As expected [6], the photodetected power at $P(\Omega)_{out}$ shows, for both post filtering setups, a dip near -2 dBm which is correlated with the sharp increase of the microwave phase shift.

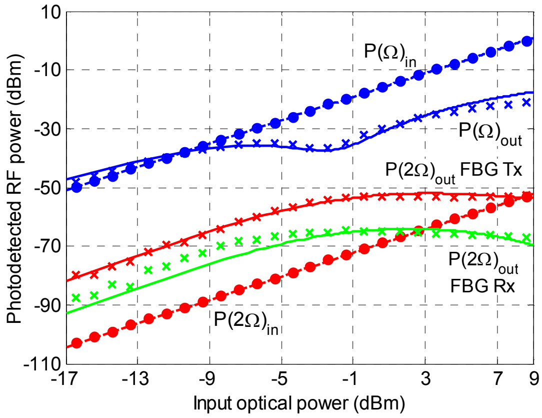


Fig. 4. Theoretical (lines) and experimental (markers) results for the photodetected RF power from the fundamental tone, P(Ω), and the second harmonic, P(2Ω), versus the input optical power. The dashed lines are the calculated harmonics before the SOA and the solid lines are the calculated harmonics after the SOA+FBG, operating in transmissium or in reflection.

4. Conclusions

We have presented a model based on the optical field that accounts for any general order of harmonic distortion in a SFL phase shifter based on CPO in a SOA device. The model has been tested against the experimental results obtained for second order harmonics showing an excellent agreement. For microwave photonic applications where large signal operation is required, we have proposed two different optical filtering implementations for the proper design of distortion-free microwave photonic phase shifters.

5. References

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