Intermodulation distortion in microwave phase shifters based on slow and fast light propagation in semiconductor optical amplifiers

Perrine Berger,1,2,* Jérôme Bourderionnet,1 Fabien Bretenaker,2 Daniel Dolfi,1 Seán Ó Dúill,3 Gadi Eisenstein,1 and Mehdi Alouini1,4

1Thales Research & Technology, Campus Polytechnique, 1 Avenue Augustin Fresnel, 91767 Palaiseau Cedex, France
2Laboratoire Aimé Cotton, CNRS-Université Paris Sud 11, Campus d’Orsay, 91405 Orsay Cedex, France
3Electrical Engineering Department, Technion, Haifa 32000, Israel
4Institut de Physique de Rennes, UMR CNRS 6251, Campus de Beaulieu, 35042 Rennes Cedex, France

*Corresponding author: perrine.berger@thalesgroup.com

Received June 1, 2010; accepted July 12, 2010; posted July 27, 2010 (Doc. ID 129214); published August 12, 2010

We show theoretically and validate experimentally the effect of filtering on the nonlinear behavior of slow and fast light links based on coherent population oscillations in semiconductor optical amplifiers. The existence of a dip in the power-versus-current characteristics for the fundamental frequency, as well as for the third-order intermodulation product, is clearly evidenced. These two dips occur at different bias currents. Their depths increase as the filtering strength of the red sideband is increased, and they completely vanish in the unfiltered case. Influence on the microwave photonics link is discussed. © 2010 Optical Society of America

OCIS codes: 250.5080, 060.5625, 070.1170.

Slow and fast light propagation in semiconductor optical amplifiers (SOAs) has been investigated extensively in recent years. Coherent population oscillations (CPOs) in SOAs are considered to be one of the most mature approaches to produce phase shifts in the microwave domain and thus could find practical applications in microwave photonics systems [1-4]. A useful method to enhance the operational frequency and the phase shift is optical filtering of the redshifted modulation sideband prior to detection [4]. Using this technique, a 360° wideband continuous phase shifter has been recently demonstrated with a cascade of SOAs [4]. The large phase shift obtained by red sideband filtering is, however, accompanied by a significant RF signal reduction at the phase jump. Optical filter also reduces the overall noise power but to a lesser extent, leading to a degradation of the output signal-to-noise ratio (SNR) [4]. Nevertheless, a combination of some degree of filtering and the largest available optical power enables large phase shifts with a moderate SNR deterioration [4].

Another important issue in evaluating the merits of the filtering approach is its effect on the linearity of the link. Indeed, similarly to the fundamental signal whose characteristics evolve with the degree of filtering, it is expected that attenuating the red part of the spectrum should affect the nonlinear behavior of the CPO-based phase shifter. The nonlinearity we consider here is the third-order intermodulation product (IMD3). This nonlinearity accounts for the nonlinear mixing between neighboring frequencies f1 and f2 of the RF spectrum and refers to the detected RF power at frequencies 2f2 − f1 and 2f1 − f2. Because these two frequencies are close to f1 and f2, this quantity is of particular importance in radar and analog transmission applications, where IMD3 is the dominant detrimental effect for microwave photonics (MWP) links [5].

This Letter presents an experimental study of the IMD3 generation in a single-stage phase shifter consisting of an SOA followed by an optical notch filter (ONF), which attenuates the redshifted modulation sideband. Fundamental RF power and IMD3 are measured for various degrees of filtering, at the typical RF frequency of 10 GHz, and numerical simulations are carried out in the same experimental conditions. On the basis of these results, we discuss the influence of the sideband filtering strength and of the SOA bias current on the spurious free dynamic range (SFDR) of the overall MWP link.

The experimental setup for IMD3 measurement is depicted in Fig. 1. The RF tones are generated by two RF synthesizers at f1 = 10 GHz and f2 = 10.01 GHz. The two RF signals are combined to drive a zero-chirp Mach–Zehnder modulator (MZM). A single-frequency tunable laser source (TLS) feeds the MZM. The optically carried signal is coupled to the phase-shifting element that comprises a commercial SOA and an ONF that includes an isolator and a fiber Bragg grating (FBG). The 3 dB spectral bandwidth of the FBG is 0.2 nm. The SOA gain and the output saturation power are, respectively, 21.3 dB and 15 dBm at 500 mA bias current.

![Fig. 1. (Color online) Experimental setup for IMD3 measurement: EDFA, erbium-doped fiber amplifier; PC, polarization controller. The redshifted sideband attenuation is varied from 0.5 dB to 24 dB (inset).](https://example.com/f1.png)

© 2010 Optical Society of America
The optical power at the SOA input was set at 10 dBm, which ensures operation in strong saturation conditions, which is favorable for phase-shifting applications [3]. The various degrees of redshifted optical sideband filtering are obtained by tuning the optical carrier wavelength with respect to the central wavelength of the notched filter (see Fig. 1 inset). Finally, to eliminate all photodetector nonlinearities, an optical attenuator is placed before the detector. The detected RF signal is then sent to a RF spectrum analyzer, which records the output RF power at the four frequencies $f_1$, $f_2$, $2f_2 - f_1$, and $2f_1 - f_2$ for IMD3 evaluation. The RF phase shift at 10 GHz is also measured using a vector network analyzer (VNA). For our measurements, we considered four different wave-lengths, that is, 4° of optical filtering (see inset of Fig. 1).

The plots reported in Fig. 2 correspond, respectively, from left to right to a redshifted sideband optical attenuation of 0.5, 14.4, 20 and 24 dB. In this figure, the input RF power $P_{RF_{in}}$ is 9 dBm, corresponding to a modulation depth of 0.17. The upper plots represent the RF phase shift measured with the VNA at the RF frequency $f_1 = 10 \text{ GHz}$ and for SOA bias currents ranging from 75 mA to 570 mA. The lower plots in Fig. 2 show the fundamental output RF power (in blue) and the IMD3 (in red) as a function of the SOA bias current. It must be noted that because input RF powers at $f_1$ and $f_2$ are equal, and $f_1$ and $f_2$ are very close, the measured RF powers at the output of the link at $2f_2 - f_1$ and $2f_1 - f_2$ on the one hand, and at $f_1$ and $f_2$ on the other hand, are also equal. Consequently, only the measurements at $f_1$ and $2f_2 - f_1$ are reported. For each plot, symbols (dots and triangles) label experimental data, whereas solid curves represent our numerical simulations. These simulations are carried out using the approach exhaustively described in [3], slightly modified to deal with electric fields rather than optical intensities in the propagation equations. We also included in the model the phase transfer function of the FBG used for sideband filtering, according to [4]. The most important result of Fig. 2 is that the theory and experiment agree remarkably to evidence the presence of a dip in power-versus-current characteristics of both the RF signal and the IMD3. Although the two dips do not occur at the same bias current (respectively, 200 mA and 120 mA for fundamental RF signal and IMD3), they behave similarly with respect to the degree of filtering. Both dips decrease as the redshifted sideband filtering diminishes and completely disappear in the absence of filtering.

As reported in our previous theoretical paper [3], a dip in the IMD3 power spectrum can actually be observed in the unfiltered case but at a lower RF frequency, typically 1–2 GHz. In all these situations, the dip in IMD3 results from a competition between MZM-induced IMD3 amplification and IMD3 generation through CPO in the SOA with these two contributions being in antiphase [3]. To understand our experimental results, we notice that CPO induces a temporal grating through the Henry factor [10]. The strength of this grating is larger than that of the gain grating. Without optical filtering, the index grating contributions for the two optical sidebands cancel each other at detection. Conversely, the index grating plays a dominant role if the redshifted sideband is suppressed [3]. As a consequence, the transition from the CPO-dominant to amplification-dominant regime occurs around 1 GHz without filtering, whereas this transition occurs around 10 GHz for maximum filtering.

To optimize phase tunability, the SOA is biased around the phase transition current, corresponding to the RF signal dip. Considering at first glance that the MWP link linearity is driven by the power ratio between the RF signal and the IMD3, it can be concluded from Fig. 2 that a moderate degree of filtering is preferable to avoid link
performance deterioration. Additionally, an interesting feature from the application point of view is the SOA current mismatch between the dips in the RF signal and in IMD3. This leads to significantly different linearity behavior of the MWP link for different SOA bias currents. This is illustrated in Fig. 3, showing the output versus input RF powers for the fundamental frequency (circles) and for IMD3 (triangles) for SOA bias currents of 110 mA (IMD3 dip, in red) and 200 mA (signal dip, in blue). One can first notice that the intercept point (IP), referring to the output RF power, such as RF signal power equals IMD3, is 8 dB larger at 110 mA than at 200 mA. Moreover, the IMD3 slope in log–log scale at 110 mA (IMD3 dip) is 4, whereas it has the common value of 3 at 200 mA. Similarly to [11], the IMD3 dip corresponds to the cancellation of the term varying with the third order of $P_{RF}$. In the expression of IMD3 using the Taylor series expansion of the MWP link power versus MZM applied voltage transfer function. For a perfect cancellation, residual IMD3 varies then with the fifth order of $P_{RF}$. Otherwise, the IMD3 slope has the asymptotic values of 3 and 5, respectively, for low and high input RF powers. The 4 slope observed here corresponds to a $P_{RF, in}$ range lying at the transition between the 3 and 5 slopes. For illustration purposes, the link noise floor in Fig. 3 is set at −100 dBm for 110 mA bias current. In a first approximation, we assume that amplified spontaneous emission filtering will reduce the noise floor at the signal dip by 6 dB [8], which is of the same order as the IP difference between 100 and 200 mA. As illustrated in Fig. 3, the SFDR (in decibels) of the link will hence increase by 12.5% when the IMD3 slope changes from 3 (signal dip) to 4 (IMD3 dip). A more detailed and quantitative discussion on noise and SFDR behavior will be given in a forthcoming paper.

To conclude, we presented an experimental investigation of the influence of the degree of redshifted sideband filtering on the linearity of a phase-shifting element based on slow and fast light propagation in an SOA. Numerical simulations were also presented. An excellent agreement is found between the model and experiments, which highlights the effectiveness of the model. Furthermore, we showed that a moderate degree of filtering (typically <15 dB attenuation) guarantees a good link linearity while preserving the RF phase-shifting range. Finally, a dip in the IMD3 power-versus-current characteristic is evidenced, very similar to the commonly observed signal dip, but at a different SOA bias current. The IMD3 dip corresponds to an SFDR improvement of more than 12%, which might be an interesting feature for high linearity MWP links.

The authors acknowledge the partial support from the Délégation Générale pour l’Armement DGA/MRIS and from the GOSPEL EC/FET project.

References