Side Mode Suppression Ratio Reduction in Mach-Zehnder Modulators Using Slow-Light Waveguides

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ABSTRACT

Slow-light waveguides are investigated to reduce the side mode suppression ratio (SMSR) of reverse-biased silicon Mach-Zehnder modulators. The SMSR of single arm-biased modulators is decreased by more than one order of magnitude at a slowdown factor of 5. This enables the reduction of SMSR without the need for high RF powers. A slow-light modulator with a slowdown factor of 4 can achieve an SMSR value of 9dB using -5dBm RF power whereas 15dB more RF power is required to achieve the same effect using standard modulators.

Keywords: Silicon photonics, Microwave photonics, Side mode suppression, Integrated optics, Modulators.

1. INTRODUCTION

The generation of different photonic waveforms has drawn a lot of attention over recent years due to its wide range of applications in radars, optical communications systems, and microwave signal processing [1, 2]. Unlike conventional electronic-based waveform generators which are bandwidth limited (< 20 GHz) [3], the new concept of microwave-photonic waveform generators uses the privilege of large bandwidths which actually meet the requirements of future high-speed electronic systems.

Flat frequency combs are usually desired for waveform generator applications so that equal power in different frequencies can be obtained. Starting from a pure phase modulation, which results in a poor flatness of the frequency pattern, so far many more complicated schemes have been implemented to increase the flatness of the frequency combs in the desired wavelength range [3, 4]. The basic element of all these designs relies on the phase modulator. In order to further achieve more flat frequency combs, it is important to have a phase modulator exhibiting side harmonics with relatively equally distributed power or in other words, with lower side mode suppression ratio (SMSR).

In this paper, the possibility of reducing the SMSR in phase modulators by using the slow-light effect is investigated. A band-edge, slow-light effect in a corrugated waveguide in one arm of a Mach-Zehnder modulator (MZM) is employed. The slow-light modulator performance has already been studied in [5, 6]. Here we will show that, compared to standard modulators, such modulators can also be used to increase the side harmonics levels.

2. MATHEMATICAL DESCRIPTION

In order to explain how slow-light modulators affect the SMSR, we start with the mathematical description of an MZM. The optical output of an MZM can be written as:

$$E_o = A(t)e^{j2\pi f_{opt}t}\left[e^{-\alpha_1 L_1}e^{j\pi\frac{V_{ap1}}{V_{\pi 1}}} + e^{-\alpha_2 L_2}e^{j\pi\frac{V_{ap2}}{V_{\pi 2}}}\right] \tag{1}$$

where A(t) is the time-domain shape of the input optical signal, $V_{ap} = V_{dc} + V_{ac}$ is applied voltage, f_{opt} is the optical frequency, L_i and α_i is the length and loss coefficient of the modulator at arm i, respectively. Due to simplicity, we assume $\alpha_1 = \alpha_2 = \alpha$, $L_1 = L_2 = L$, $V_{ap1} = V_{dc} + V_m \sin(2\pi f_{RF} t)$, and $V_{ap2} = V_{dc}$. After Jacobi Anger expansion, the detected signal at the photodiode can be found as:

$$I(t) = E_o(t)E_o(t)^* =$$
$$2A(t)^2 e^{-2\alpha L}[1 + B J_0(C) + 2B\sum_{n=1}^{\infty} J_{2n}(C)\cos(2n\omega_m t)$$
$$-2D\sum_{n=1}^{\infty} J_{2n-1}(C)\sin((2n-1)\omega_m t)] \quad (2)$$

where $B = \cos\left(\pi V_{DC}\left(\frac{1}{V_{\pi1}} - \frac{1}{V_{\pi2}}\right)\right)$, $C = \left(\frac{\pi V_m}{V_{\pi1}}\right)$, $D = \sin\left(\pi V_{DC}\left(\frac{1}{V_{\pi1}} - \frac{1}{V_{\pi2}}\right)\right)$, and $J_n(x)$ is the Bessel function of the first kind. From equation (2), it can be found that the SMSR for even and odd harmonics are changing as:

$$SMSR|_{even} = \frac{1 + BJ_0(C)}{2BJ_{2n}(C)} \quad (3)$$

$$SMSR|_{odd} = -\frac{1 + BJ_0(C)}{2\sqrt{1-B^2}J_{2n-1}(C)} \quad (4)$$

where SMSR is defined as the ratio of the DC component to even and odd components of the output current of the photodiode. The SMSR change versus different RF power is sketched in Fig 1(left) for the first six harmonics. As can be seen, the SMSR reduces as the RF power increases (or equivalently, as the parameter C increases).

It was shown that in a slow-light modulator, the modulation efficiency decreases at slowdown factors higher than unity [5]. Assuming the constant RF power, the increased parameter C that resulted from employing the slow-light effect can also lead to a reduction in SMSR.

3. NUMERICAL AND EXPERIMENTAL RESULTS

The analytical approach, explained above, shows that the slowdown factor mitigates the SMSR. A complete numerical model, however, must consider all existing effects. It is known, for example, that the voltage required to achieve π phase shift, e.e., V_π, can be obtained from the carrier concentration changes in the phase shifter which, based on Soref's equations [6], impose extra nonlinearities on the problem. Here the semi-analytical model has been used for the estimation of V_π. In this modeling, the effect of slow-light is also included by using the slowdown factor which indicates the group-index enhancement and also the slow-light loss coefficient which considers the added loss of the band-edge in the slow-light waveguide [7-10]. In order to study the SMSR behavior, the results are used as the input to a Mach-Zehnder modulator. The parameters of the modulator used in the simulations are as follows: N_A=N_D=5×10^{17} cm^{-3}, L_1=L_2=1 mm, V_{DC}=-2 V where N_A, N_D are acceptor and donor doping concentration and V_{DC} is the DC bias voltage. The modulation frequency, f_{RF} is 15 GHz [5]. The harmonic generation with different RF power is numerically studied as shown in Fig 1(right).

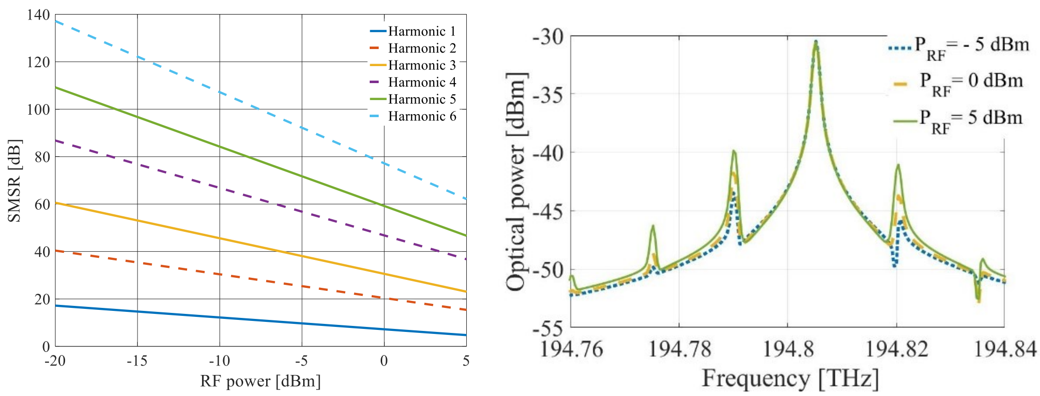

Figure 1. (left) Side mode suppression ratio of different harmonics versus RF power, (right) simulation and measurement results for the generation of the first two harmonics.

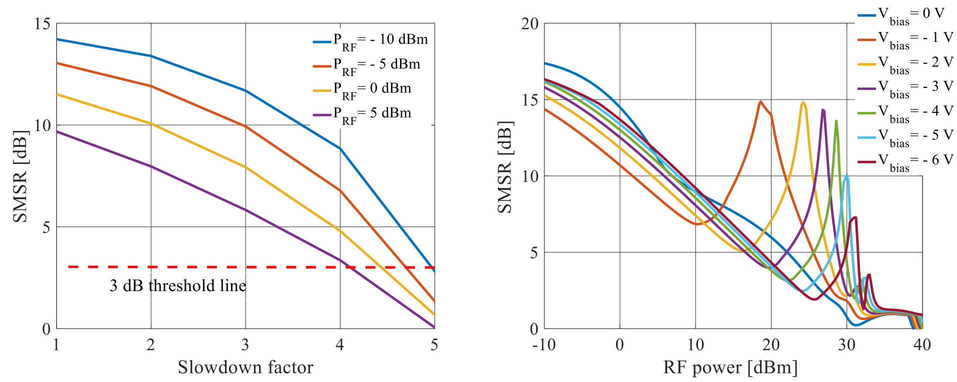

Figure 2. (left) Enhancement of the side mode suppression ratio using the slow-light effect, quantified by the slowdown factor, (right) Required RF power for reducing the SMSR of a standard modulator.

The frequency range of the experiment is set in a way that the modulator with corrugated waveguides operates at the slow-light regime. It also can be observed that the harmonics' powers are increased by increasing the amount of applied RF power. The slow-light effect on enhancing the SMSR is investigated with the numerical model. In this model, the Soref equation is used to find the loss and the phase shift induced by the applied voltage. Fig 2(left) shows the SMSR mitigation for the first harmonic only. It states that the SMSR decreases to below the 3 dB threshold for a slowdown factor of 5. Compared to non-slow-light modulators, a higher amount of RF power is required to decrease the SMSR to the same value as in Fig 2 (left). According to the simulations, an RF input power of 30 dBm is needed for a standard modulator to reach the 3 dB SMSR of a slow-light modulator with a slowdown factor of five, operating with -10 dBm RF input power. Thus, for the slow-light modulator, the RF input power is four orders of magnitude lower. The SMSR of a standard modulator versus input RF power is illustrated in Fig 2(right).

4. Conclusions

It has been shown that slow-light modulators can decrease the required voltage for a π radian phase shift by increasing the slowdown factor. Furthermore, the possibility of reducing the SMSR of different harmonics using slow-light modulators has been numerically studied. It was shown that the SMSR decreases by an order of magnitude if the modulator was employed at a slowdown factor of 4 by using 15dB less RF power at the same time. The harmonic generation in a slow-light modulator has been experimentally characterized.

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