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

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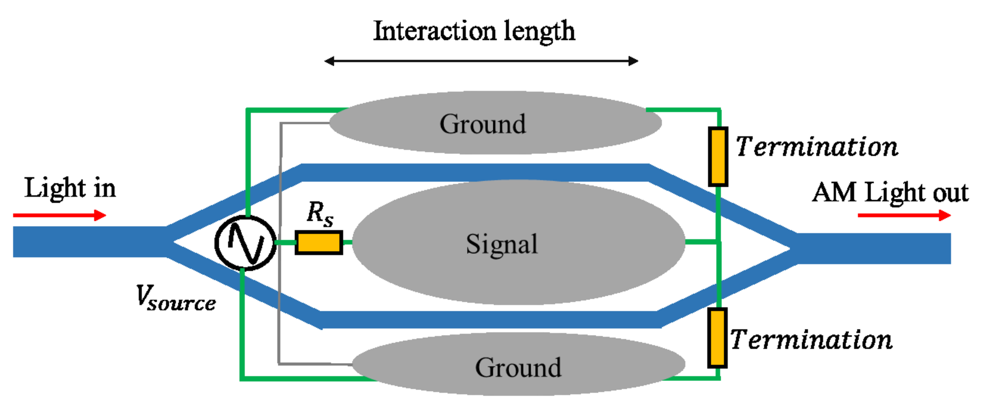
- To generate high-frequency micro- or millimeter wave signals, higher harmonics of an intensity modulator can be superimposed in a photodiode. Usually, this requires very high RF input powers.
- Slow-light waveguides are investigated to reduce the side mode suppression ratio (SMSR) of reverse-biased silicon Mach-Zehnder modulators (MZM) in simulation and experiment.
- It is reported that the SMSR of single arm-biased modulators can be decreased by more than one order of magnitude at a slow-down factor of 5. This enables the reduction of SMSR without the need for high RF powers.

Side Mode Suppression Ratio in MZMs

The optical output of an MZM can be written as:



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

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:

$$I(t) = E_o(t) E_o(t)^* =$$

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

In which:

$$B = \cos\left(\pi V_{DC}\left(\frac{1}{V_{\pi 1}} - \frac{1}{V_{\pi 2}}\right)\right) \quad C = \left(\frac{\pi V_m}{V_{\pi 1}}\right) \quad D = \sin\left(\pi V_{DC}\left(\frac{1}{V_{\pi 1}} - \frac{1}{V_{\pi 2}}\right)\right)$$

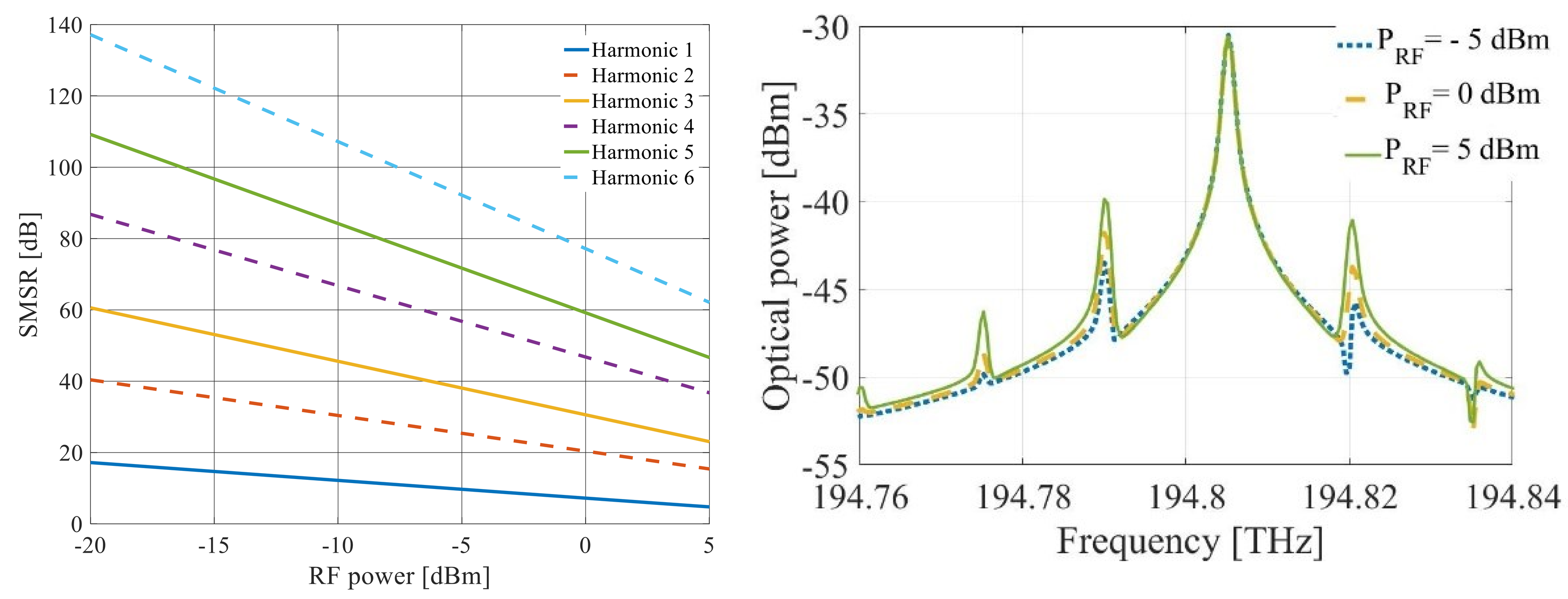
and $J_n(x)$ is the Bessel function of the first kind.

SMSR is defined as the ratio of the DC component to even and odd components of the output current of the photodiode.

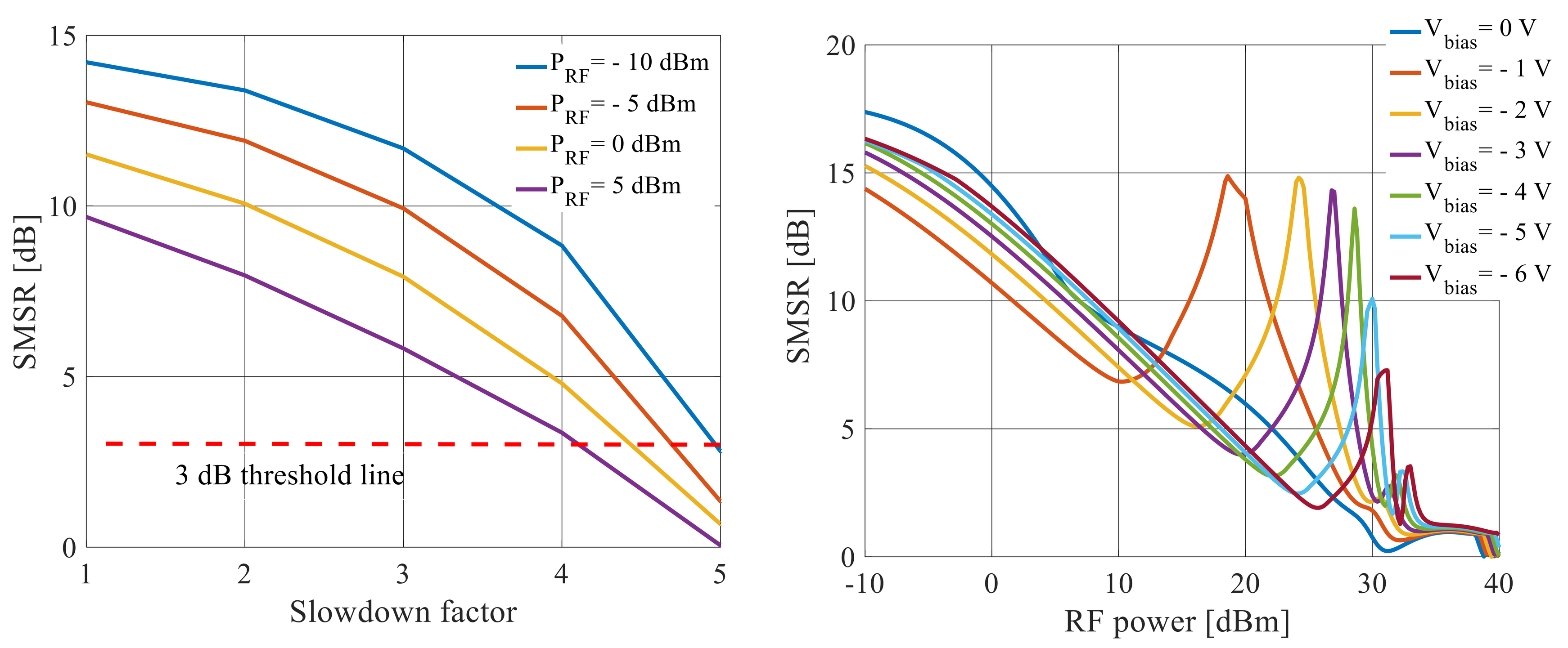
$$SMSR|_{even} = \frac{1 + BJ_0(C)}{2BJ_{2n}(C)} \qquad SMSR|_{odd} = -\frac{1 + BJ_0(C)}{2\sqrt{1 - B^2} J_{2n-1}(C)}$$

Simulation and Experimental Results

The parameters of the modulator used in the simulations are $N_A = N_D = 5 \times 10^{17}\ cm^{-3}$ as acceptor and donor doping, $L_1 = L_2 = 1$ mm and a DC bias voltage of $V_{DC} = -2$ V. The modulation frequency is $f_{RF} = 15$ GHz.



SMSR of different harmonics versus RF power on the left, and simulation and measurement results for the generation of the first two harmonics on the right.



Enhancement of the SMSR using the slow-light effect, quantified by the slow-down factor on the left and the required RF power for reducing the SMSR of a standard MZM on the right.

Conclusion

- Slow-light modulators can decrease the required voltage for a π radian phase shift by increasing the slow-down factor.
- The SMSR decreases by an order of magnitude if the modulator is employed at a slow-down factor of 4 by using 15 dB less RF power at the same time.

Acknowledgements
This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - JAM2401/11-2; SCHN716/15-2.

References

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