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# Silicon Photonics for millimeter-Wave Generation: an Energy-Efficiency Analysis

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Over the next decade, the bandwidth of wireless networks will continue to grow exponentially due to an increasingly interconnected and 'smart' environment. Current wireless frequency bands will not have enough capacity and a move towards the millimeter-wave (mmW) bands (30 GHz – 300 GHz) is required for 5G wireless networks. However, at these higher mmW carrier frequencies, the use of all-electronic solutions becomes increasingly inefficient and, hence, prohibitive.

Microwave photonics offers the bandwidth and a potentially seamless integration with the fiber-wireless technology (Fi-Wi). For example, 100 Gbps wireless transmission has been shown in the W-band [1]. Various techniques have been reported to generate the mmW-carrier in the photonic domain. One particularly promising technique is to use the comb generated by modulating a continuous-wave laser signal [2]. By filtering two non-adjacent comb lines, a beating signal is generated that has a frequency that is an integer multiple of the electrical modulator driving signal. In this way frequency multiplication is achieved using microwave photonics.

However, these experiments are typically done using off-the-shelf lithium-niobate modulators. In real-world and ubiquitous wireless systems, cheaper and more compact solutions are required. Photonic integration technology is well-placed to address these requirements. In particular silicon photonics has the advantage of low cost at large volume, potential integration with CMOS electronics, and mature system-in-package and system-on-chip technologies. Silicon-based modulators, however, are not ideal phase modulators, like lithium-niobate based modulators, and existing comb generation paradigms and techniques cannot be used for silicon modulators.

In this work we present a novel tool to simulate comb generation using silicon modulators, starting from a single-waveguide phase modulator configuration. The main aim of the tool is to provide insight in the overall energy-efficiency of the mmW-generation process. This is done by using realistic parameters for silicon modulators based on the carrier effect. We include voltage-dependent loss $\alpha(V)$, which is ignored for field-effect-based modulators, and we assume a non-linear dependency of the phase-shift $\Delta\varphi(V)$ on the voltage. Furthermore we include modulator bandwidth and energy-efficiency of the electronic radio-frequency (RF) drivers, i.e., the microwave oscillator, into our tool.

For silicon phase modulator lengths of 3 mm, with a full set of specifications as presented in [3], the efficiency of comb line – or harmonic – generation is shown in Fig. 1(a). It can be seen clearly that the generation of higher harmonics becomes increasingly inefficient. This would indicate that frequency multiplication by large factors is inefficient. However, as shown in Fig. 1(b,c), the bandwidth of the modulator is limited and the efficiency of electronic RF drivers, or oscillators, decreases for higher frequencies. These figures clearly show that a trade-off is required between electrical drive frequency and microwave photonic frequency multiplication when, e.g., W-band output frequencies are targeted.

An initial result based on a full analysis using our simulation tool is shown is in Fig. 2. In this figure, the efficiency is shown for 30-GHz mmW-generation, using frequency multiplication with factors 2× up to 10×. This is achieved using the first up to fifth pair of harmonics, respectively. The highest efficiency point at frequency quadrupling (4×) clearly indicates that we have to make design trade-off between electrical driving frequency and multiplication factor, which is the main conclusion of this work. This approach can potentially be further optimized by cascading two or more silicon phase modulators.

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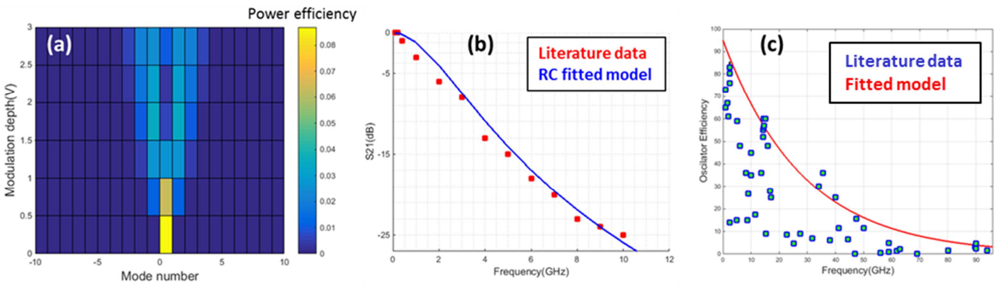


**Fig. 58. (a) Simulated efficiencies for comb line generation, using modulator parameters from [3]; (b) bandwidth of the modulator [3]; (c) microwave oscillator efficiency based on a literature study.**

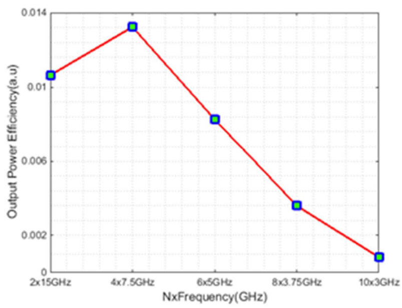


**Fig. 59. Output power efficiency of 30-GHz mmW-generation using the first five pairs of comb lines, or harmonics.**

References

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