

Optical Sideband Modulation in Silicon Photonics Platform Using Mach-Zehnder Interferometers

Muhammad Fasih, Hyeonho Yoon, Namhyun Kwan, Junhyeong Kim, Jinhyeong Yoon, Rabiul Islam Sikder, Hamza Kurt and Hyo-Hoon Park

Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu 34141, Daejeon, Korea.

muhammad.fasih@kaist.ac.kr, exhyho@kaist.ac.kr, kronicle11@kaist.ac.kr, wnsud@kaist.ac.kr, ymyyjh@kaist.ac.kr, rabiulsikder@kaist.ac.kr, hamzakurt@kaist.ac.kr, parkhh@kaist.ac.kr.

Abstract— Optical sideband modulation is a useful technique used in applications like radio-over-fiber (RoF) systems for compensation of chromatic dispersion, wavelength division multiplexing and even LiDAR. Sideband can be modulated in different ways depending on the required application. In this paper, we present and compare different sideband modulation methodologies which offer advantages in terms of reduced fabrication complexity, better carrier suppression and, efficient sideband, carrier and higher order sideband suppression ratios. Optical sideband modulation using interferometers like Mach-Zehnder Interferometer (MZI) offer advantages over techniques like optical filtering because their operation is independent of frequency. We present modulation techniques using single dual-drive MZM (DD-MZM) dual-parallel single-drive MZM, dual-parallel dual-drive MZM (DP DD-MZM) with 2 RF modulation signals and dual-parallel dual-drive MZM with 4 RF modulation signals, in simulation.

Keywords— Optical sideband modulation, Double sideband modulation, Single sideband modulation, Single sideband suppressed carrier modulation, Silicon photonics.

I. INTRODUCTION

Optical sideband modulation involves suppression of either upper or lower sideband, higher order sidebands and even carrier in some cases. It is widely used in a variety of significant applications which include compensation of chromatic dispersion [1], wavelength division multiplexing [2], [3], high frequency applications, optical filtering [4], and even light distancing and ranging (LiDAR)[5], [6]. The chromatic dispersion can be alleviated in radio-over-fiber (RoF) systems by transmission of a single sideband signal and frequency shifting can be obtained in case of frequency modulated continuous LiDAR using single sideband suppressed carrier modulation. Silicon photonic modulators offer advantages over other counterparts, such as Lithium Niobate, because of their compatibility with CMOS process and wide adaption in photonics domain. There is a need for optical single sideband modulation techniques using modulators based on silicon photonics.

Many techniques have been implemented for the generation of an optical sideband modulated signal. Optical single

sideband (OSSB) modulation can be obtained by optical filtering which may use notch filters having Bragg gratings of Brillouin scattering [7]. However, use of filters can be complicated and reduce the bandwidth of the system. Surface acoustic waves have also been used to generate OSSB signal [8] but it can be tricky and cumbersome to implement such systems because the setup requires fabricated interdigital transducers to generate the acoustic waves. Ring modulators [9] have also been used to generate single sideband signal with carrier but usually, it cannot be used in applications in which carrier need to be suppressed.

Mach-Zehnder interferometer-based modulators offer advantages over other techniques because of their simple operation, ease in fabrication, wide bandwidth and independent of frequency operation. Different types of Mach-Zehnder modulator (MZM) configurations have been used for sideband modulation. A single dual-drive MZM was used for single sideband (SSB) modulation [1]. Single sideband suppressed carrier (SSB-SC) modulation using dual-parallel dual-drive MZM (DP DD-MZM) has also been demonstrated on Lithium Niobate substrate [10]. These demonstrations have been performed at different frequencies, substrates and applications. In this paper, we present different MZM configurations for the sideband modulation under similar simulation conditions, same fabrication substrate of silicon and matching carrier and modulation frequencies to make a fair comparison and to determine the advantages and disadvantages of each of them.

II. METHODOLOGY

Different techniques based on the level of complexity to fabricate is presented in this section. OSSB signals can be generated either by a single dual-drive MZM (DD-MZM), dual-parallel single-drive MZM (DP-SD-MZM) or dual-parallel dual-drive MZM (DP-DD-MZM). The simulations have been performed in Lumerical Interconnect.

A. Single Dual-drive MZM

Figure 1 shows the schematic of a single dual-drive MZM. RF modulation signal is applied to each of the two arms with a 90° electrical phase shift using a quadrature hybrid coupler and

an optical phase shift of 90° is also applied as referred in the schematic by green box. For this research article, the RF signal applied is of 5 GHz and optical carrier frequency is of 193.4 THz (1550 nm) unless specified otherwise.

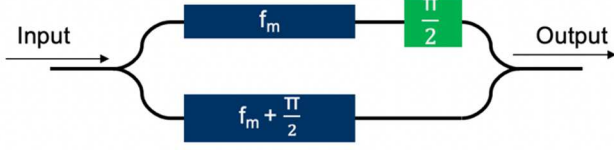


Figure 1. Schematic of single dual-drive MZM.

This scheme produces a single sideband (SSB) signal with carrier which will be further discussed in the results section.

B. Dual-parallel Single-drive MZM

Figure 2 shows the structure for the dual-parallel single-drive MZM. RF signal with a 90° phase shift is applied to one of the arms of each sub-MZM and both arms of the sub-MZM have an optical phase shift of 180° and there is a 90° optical phase difference between the two arms of the combiner.

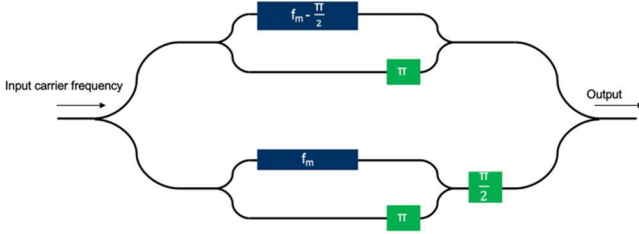


Figure 2. Schematic of dual-parallel single-drive MZM.

C. Dual-parallel Dual-drive MZM with 2 Modulation Signals

The schematic is shown in Figure 3, where it can be seen that RF signal with an electrical phase difference of 90° is applied to the two arms of each sub-MZM. There is optical phase difference of 180° between the two arms of each sub-MZM and 90° between the two outer arms.

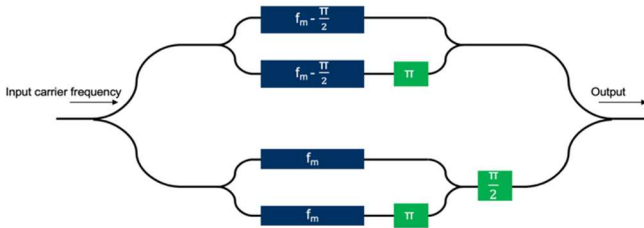


Figure 3. Schematic of dual-parallel dual-drive MZM with 2 modulation signals.

D. Dual-parallel Dual-drive MZM with 4 Modulation Signals

Figure 4 shows the schematic of the dual-parallel dual-drive MZM but this one has four RF modulation signals applied to each of the arms of the sub-MZM. This configuration increases the system complexity but it offers advantages in terms of

sideband, carrier and higher order sidebands suppression, which will be explained in the results section.

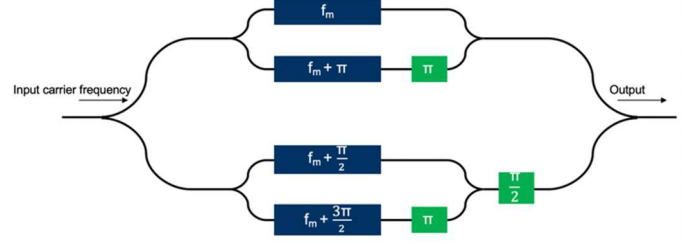


Figure 4. Schematic of dual-parallel dual-drive MZM with 4 modulation signals.

The RF signals applied to each of the arms of sub-MZMs from top to bottom are with an electrical phase shift of 0° , 180° , 90° and 270° respectively. These RF phase shifted signals can be implemented using external or on-chip quadrature and 180° hybrid couplers.

III. RESULTS AND DISCUSSION

The results of all the schemes discussed in the methodology section are discussed here in terms of sideband suppression ratios, carrier suppression ratios and higher order sideband suppression ratios with respect to the desired upper sideband (USB). As discussed earlier, the simulations have been performed at a carrier wavelength of 1550 nm (193.4 THz) and an RF modulation frequency of 5 GHz.

A. Single Dual-drive MZM

This is the simplest of all the structures discussed in this article with just a single dual-drive MZM and two RF signals with 90° phase shift with a quadrature hybrid coupler is applied to both of the arms, and both of the arms have an optical phase difference of 90° , as shown in Figure 1. The results are shown in Figure 5. Our desired sideband in this case is upper sideband (USB) at frequency $f_c + f_m$. It produces a SSB signal with an upper to lower sideband (LSB) suppression ratio of 30.3 dB while USB to higher order sideband (HOSB) suppression ratio of 14.5 dB.

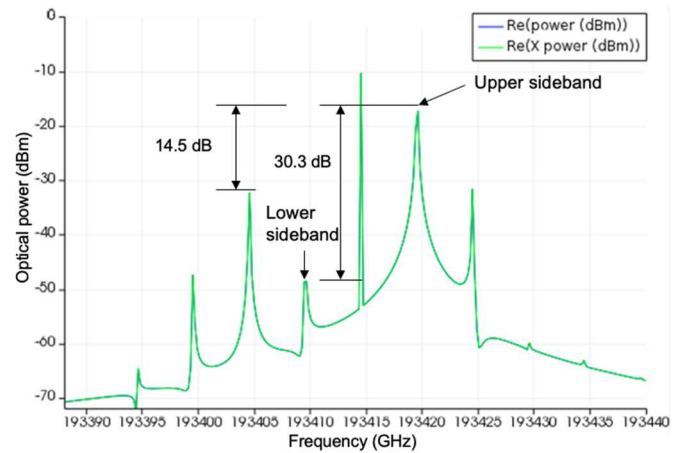


Figure 5. SSB modulation using single dual-drive MZM.

B. Dual-parallel Single-drive MZM

The results for DP-DD-MZM configuration are shown in figure 6. In this case, the complexity increases as there are two sub-MZMs, but it offers better results as compared to the previous scheme. It produces an SSB-SC signal having a sideband suppression ratio (SSR) of 37.2 dB, sideband to carrier suppression (SCSR) of 6 dB and higher order sideband suppression ratio of 13.8 dB.

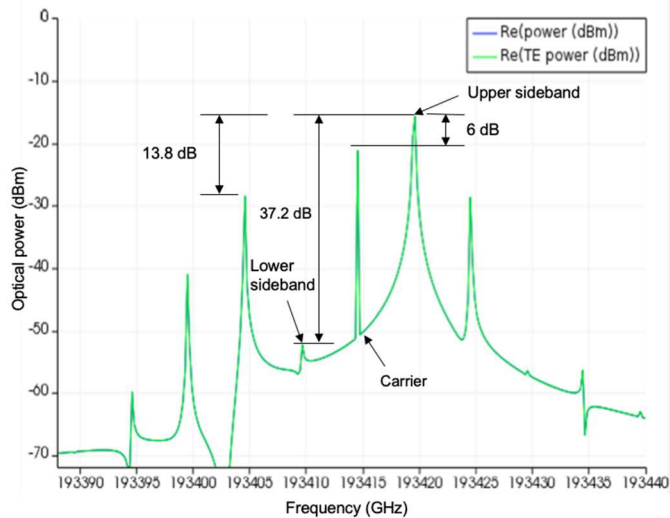


Figure 6. SSB-SC modulation using dual-parallel single-drive MZM.

C. Dual-parallel Dual-drive MZM with 2 Modulation signals

The results are shown in Figure 7. It can be observed that in this case, an SSR of 34.1 dB, SCSR of 35.46 dB and higher order suppression ratio of 6.1 dB. The main drawback offered by this configuration is due to very low suppression ratio of higher order sidebands with respect to the desired USB. Another drawback of this scheme is that all the sidebands at different frequencies suffer great attenuation.

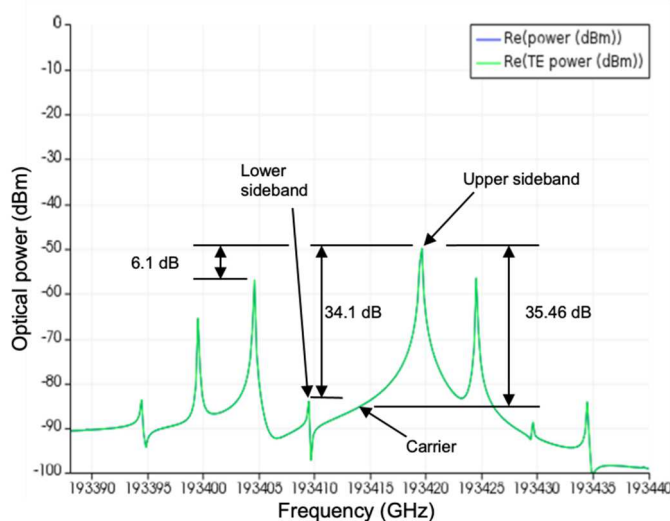


Figure 7. SSB-SC modulation using dual-parallel dual-drive MZM.

D. Dual-parallel Dual-drive MZM with 4 Modulation Signals

This scheme has the highest complexity level of all the schemes discussed but it offers better results in terms of all the suppression ratios. Figure 8 shows the results. SSR of 36 dB, SCSR of 36.1 dB, and higher order suppression ratio of 25.45 dB with respect to the desired USB can be observed.

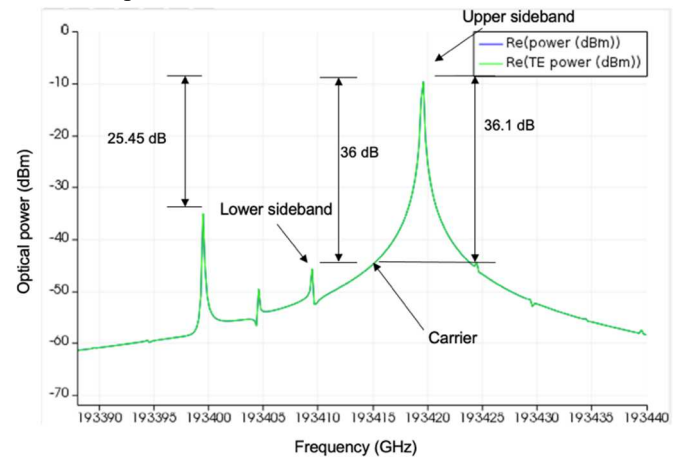


Figure 8. SSB-SC modulation using dual-parallel dual-drive MZM.

E. Comparison of all the Configurations

A comparison for all the configurations for optical sideband modulation in this paper has been presented in Table 1. As mentioned earlier, all the simulations have been performed at a carrier frequency of 1550 nm and RF modulation frequency of 5 GHz.

TABLE 1. COMPARISON OF PARAMETERS FOR DIFFERENT CONFIGURATIONS OF MZM.

	Single DD-MZM (dB)	DP-SD-MZM (dB)	DP-DD-MZM with 2 modulation signals (dB)	DD-DP-MZM with 4 modulation signals (dB)
SSR	30.3	37.2	34.1	36
SCSR	N/A	6	35.46	36.1
HOSSR	14.5	13.8	6.1	25.45

Where SSR is sideband suppression ratio, SCSR is sideband to carrier suppression ratio, HOSSR is higher order sideband suppression ratio, DD-MZM represents dual-drive MZM, DP-SD-MZM represents dual-parallel single-drive MZM and DP-DD-MZM represents dual-parallel dual-drive MZM.

It can be observed that DD-DP-MZM scheme offers the best results overall but on the cost of a bit more complexity. One solution for the four phase shifted RF signals can be their on-

chip generation [11]. Depending on the application, a specific configuration from the table can be chosen.

This study can also be considered for observing the comparison among the state-of-the-art techniques. Several research groups have used one of these similar techniques to generate optical signals according to their targeted application. Some examples include the generation of FMCW chirp signal using dual-parallel MZM as given in Ref. [6] and the generation of optical single sideband signal using single dual-parallel modulator ring modulator as described in Ref. [11], both of which can be referred to the third and first techniques discussed in this article for making a general comparison.

IV. CONCLUSIONS

Optical sideband modulation is an important technique which has uses in optical communication, optical filtering and LiDAR applications. Using Silicon-based Mach-Zehnder interferometers for the process of sideband modulation offer advantages in terms of wide bandwidth of operation, and ease of fabrication and integration because of compatibility with widely used CMOS process. Different techniques have been compared in this article for generating SSB and SSB-SC signals. It was observed that dual-parallel dual-drive MZM configuration offers the best results on cost of a bit more complexity. The robustness of the system against phase and amplitude imbalances can be inspected and feedback mechanism can be integrated into the design.

ACKNOWLEDGMENT

This research is supported by the development of smart 3D image sensors based on silicon optical phased array program (N01210513).

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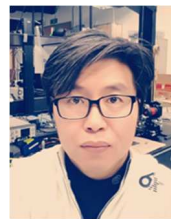
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Muhammad Fasih received his M.S. degree in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST) – Daejeon, Korea in August, 2019. He got his B.S. degree in Electrical Engineering from National University of Sciences and Technology – Pakistan in June 2017. His research is focused on nano-photonics and silicon photonics.



Hyeonho Yoon received his Ph.D. degree in Electrical Engineering from KAIST – Daejeon, Korea in 2019. He is now a research professor at KAIST.



Namhyun Kwan received his B.S. degree in Electrical Engineering from KAIST – Daejeon, Korea, in 2017. He is now an integrated M.S. leading to Ph.D. student in department of Electrical Engineering at KAIST.



Junhyeong Kim received his B.S. degree in Electrical Engineering from KAIST – Daejeon, Korea, in 2020. He is now an M.S. student in department of Electrical Engineering at KAIST.



Jinhyeong Yoon received his B.S. degree in Electrical Engineering from Kyung Hee University - Korea, in 2020. He is now an integrated M.S. leading to Ph.D. student in department of Electrical Engineering at KAIST.



Rabiul Islam Sikder is currently a Ph.D. student at KAIST – Daejeon, Korea. He received his B.S degree in Electrical and Electronic Engineering from North South University, Bangladesh, in 2018. His research is focused on nano-photonics including the design and analysis of nano-photonics materials.



Hamza Kurt received his Ph.D. degree in Electrical and Computer Engineering from Georgia Institute of Technology - USA in 2006, and M.S. degree in Electrical Engineering from University of Southern California - USA in 2002. He got his B.S. degree in Electrical and Electronics Engineering from Middle East Technical University - Turkey in 2000. He is currently a professor at the department of Electrical Engineering and director of MetaPhotonics Research Lab at KAIST, Korea.



Hyo Hoon Park received M.S. and Ph.D. degree from department of Materials Science and Engineering from KAIST, Korea, in 1982 and 1985, respectively. From 1985 to 1986, he was a post-doctoral scholar from Stanford University. He was working for ETRI (Electronics Telecommunications Research Institute) since 1997. Since 1998, he is a professor of Electrical Engineering at KAIST. His current research interests include silicon nanophotonics for microprocessor-memory interfaces, 3D chip interconnection, phased-array antenna etc.