Quadrature Hybrid Circuit for the Optical Single Sideband Modulation of microwave signals

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Abstract: Optical Single Sideband modulation of RF signals at 2 GHz has been experimentally observed. The signal was driven into a microwave circuit that incorporates a quadrature hybrid and a bias network and redirected to a dual-drive Mach-Zehnder modulator. The design of the microwave circuit by using commercial ADS software is presented, as well as the resulting sideband rejection ratio of 20 dB recorded through heterodyne spectrum measurements of the optical modulated signal.

I. INTRODUCTION

In order to be able to transmit information at long distances using optical fibers, it is interesting to reduce the losses caused by the chromatic dispersion in our fibers. This reduction can be achieved by the elimination of one of the bands of the modulated signal inducing a single sideband (SSB) modulation, which is of interest in a wide range of applications [1].

It can be seen that by using a dual-drive Mach-Zehnder modulator (DD-MZM), under the appropriate operation conditions produces the desired single sideband [1]. The goal of our project is to design a microwave system with ADS that fulfills the required specifications to observe the SSB modulation in a laboratory setup.

The paper is organized as follows: firstly in Section II we will describe the fundamental mathematical concepts related to DD-MZM and quadrature hybrid as well as the required conditions to achieve a SSB. Right after, in Section III, the setup of the experiment we made to calculate the extra phase induced by the DD-MZM available is presented. By incorporating an electrical phase shifter to our hybrid and an encapsulated bias-t-network we were able to know the phase difference in between the inputs of our DD-MZM. In Section IV we made a detailed description of the design and the implementation of our microwave circuit, presenting our experimental results in section V to confirm the Optical Single Sideband modulation at 2 GHz. The paper ends with a concluding section.

II. FUNDAMENTALS

2.1 Dual-drive Mach-Zehnder

A dual-drive Mach-Zehnder modulator is modeled as seen in figure1. The entrance of this optical device comes from a continuous wave (CW) signal of a laser of amplitude A and frequency ω_0. In order to obtain an optical single sideband modulation, the phase of each branch is modulated by an RF signal with frequency ω_{RF} and amplitude V_{RF} but with a phase difference of θ. In addition, one of the branches is biased with a DC current of amplitude V_B. As the MZM has a switching voltage of V_π, the final expressions need to be normalized, meaning that : $\alpha = \pi V_B / V_\pi$ and $\beta = \pi V_{RF} / V_\pi$.

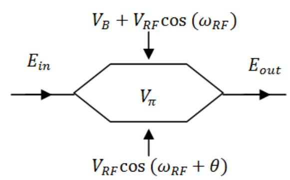

FIG.1: Model of a dual-electrode MZM

$$E_{out}(t) = \frac{A}{2}[\cos(\omega_0 t + \alpha + \beta\cos(\omega_{RF} t)) + \cos(\omega_0 t + \beta\cos(\omega_{RF} t + \theta)]$$

The previous equation can be expressed with phasorial notation as seen in the next equation:

$$E_{out} = Re[E'_{out} e^{j\omega_0 t}]$$

And then be expanded in a Bessel functions series [3]. Due to the fact that the amplitude of the modulating signal is usually low compared to the switching voltage, the small-signal approximation may be applied, allowing to neglect terms up to second order. The complex expression of the optical field at the DD-MZM is then written as:

$$E'_{out} = J_0(\beta)[1 + e^{j\alpha}] + 2jJ_1(\beta)[\cos(\omega_{RF} t)e^{j\alpha} + \cos(\omega_{RF} t + \theta)]$$

Here J_0 and J_1 are the zero and first order Bessel functions respectively. By setting α and θ equal to 90 °, we then obtain a final expression that is equal to:

$$E_{out}(t) = \frac{A}{2}[J_0(\beta)\cos(\omega_0 t) - J_0(\beta)sin(\omega_0) - 2J_1(\beta)\cos(\omega_0 t - \omega_{RF} t)]$$

And the power spectral density which is given by the Fourier transform [4] of the autocorrelation of E_{out} is given by:

$$S_{E_{out}}(\omega) = \frac{A^2}{4} J_0^2(\beta)\pi\delta(\omega+\omega_0) + \frac{A^2}{2} J_1^2(\beta)\pi\delta(\omega+(\omega_0-\omega_{RF})$$

As it can be seen, the first term corresponds to the carrier signal and the second term to one of the modulated bands (if we has chosen an electrical phase difference of -90° we would have got the other band).

2.2 Quadrature (90°) Hybrid

One of the fundamental elements of our circuit is the Branch-line or quadrature (90°) Hybrid whose model is represented in figure 2. It is commonly designed using microstrip lines. The value of the reference impedance Z_0 is 50 ohms because it is the common port resistance value in RF circuits.

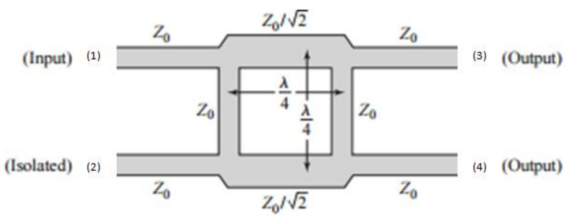

FIG.2: Model of the Quadrature(90°) Hybrid

By using an even-odd decomposition [2], it can be shown that for the same characteristics referred to the figure, the scattering matrix is

$$[s] = \frac{-1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & j & 1 \\ 0 & 0 & 1 & j \\ j & 1 & 0 & 0 \\ 1 & j & 0 & 0 \end{pmatrix}$$

What this matrix indicates us is that the signal that enters in the port labeled 'input' while port 'isolated' is terminated is equally divided between the two 'output' ports, with a phase difference of 90°. With this setup the upper band is cancelled while if we use port 2 as the input with port1 terminated, it would be the lower band. Identical results are obtained if we use 3 and 4 as inputs due to the symmetry of the device.

III. SSB TEST

In order to precisely get the 90º of phase difference in the Mach-Zehnder RF ports, we prepared a test, using a quadrature (90°) hybrid, a phase shifter, a laser, a RF signal generator, an encapsulated bias-t network, a DC generator, a polarizer and a BOSA. The high resolution Optical Spectrum analyzer based on the Brillouin effect was required in order to have enough optical resolution to distinguish the different bands.

The main objectives of this test are:

- Making sure that a circuit with a quadrature hybrid and the proper DC bias value in the DD-MZM will be able to erase one of the side bands of the modulation.
- Measure any possible phase shift in our system that would risk the 90º phase difference we need, so that we can take care of it in the final design through a phase shifter section.

As seen in FIG 3, the output of the laser source, with 5 dBm and a 1550nm wavelength, is connected to the optical input of the Fujitsu DD-MZM. Due to polarization dependence of the Pockel's electro-optical effect [5] responsible for the electrical modulation of optical signals: the input to the DD-MZM is a polarization preserving fiber. An optical polarization control device is therefore used after the laser to reduce the loss due to polarization mismatch. The RF signal at 2 GHz is connected to the port 1 of the hybrid circuit that follows the scheme in Figure 2, port 2 is terminated with a reference load while ports 3 and 4 are connected respectively to a bias-t network and a phase shifter, and then to each one of the interferometric arm RF inputs of the DD-MZM .The output of the DD-MZM was connected to the BOSA in order to monitor the spectrum of the modulated optical signal.

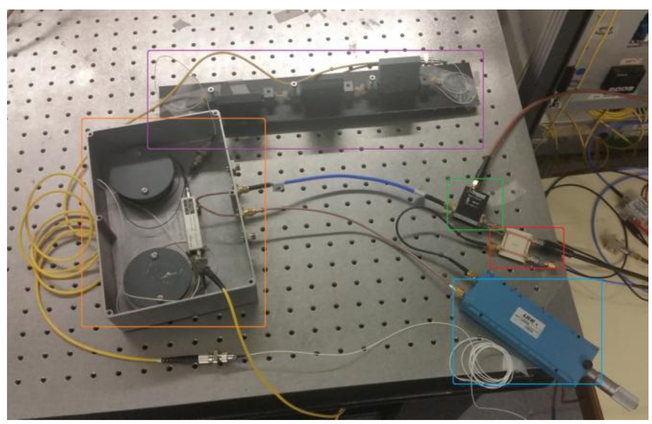

FIG.3 (Color online) The test circuit we used. Its main parts are, from left to right: the Mach-Zehnder (orange), the polarization control (violet), the Bias network (green), right at its side: the hybrid (red) and finally the phase shifter (blue).

The first step was to determine the required bias for an optical 90º degrees difference between both arms of the interferometer. We did this by monitoring the optical power at the output of the DD-MZM without the RF signal. We measured the DC bias required to change from a maximum to a minimum optical power level, i.e. the half-wave voltage V_π. The measured optical extinction ratio between those two levels was 20 dB and the V_π voltage measured was 3.6V. According to this result, in order to obtain an SSB we need to set the bias to 1.8V.

We then connected the RF signal and adjusted the phase shifter while monitoring the BOSA screen until we observed cancellation of one of the sidebands. As seen in the screenshot of Figure 4 more than 20 dB extinction was achieved between sidebands.

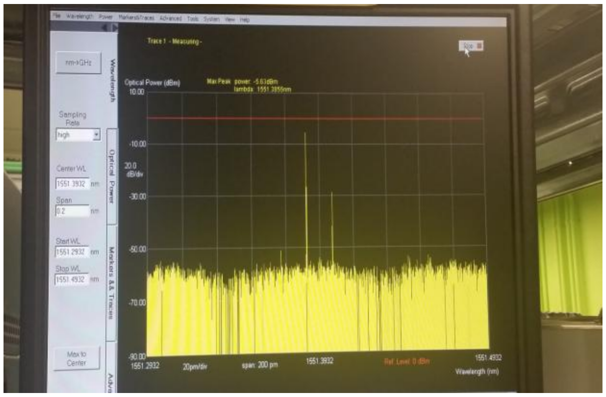

FIG 4. (Color online). BOSA screenshot obtained in the setup of FIG 3: the result of the SSB test.

With that test we were able to see that the MZM induces an extra phase to our circuit. Thanks to an Agilent Network Analyzer, we measure that an extra 17° are needed in order to achieve the SSB modulation. This effect is due to the fact that the cables that drive the RF signal to the electrodes are different.

IV. ADS DESIGN

The design of our microwave circuit is divided into three blocs as seen in figure 5. An additional length between the hybrid output ports which was adjusted to match the phase shift between both DD-MZM and RF connectors is added (17º as given by the experimental test explained in the previous section). A sharp tuning process was needed in order to add microstrip line to obtain those 17º and yet manage to maintain the desired distance between the two ports connected to the DD-MZM.

The substrate used corresponds to Rogers 4003 [5]. LineCalc was used to adjust the widths and lengths of the microstrip lines to ensure the desired impedances and electrical lengths at 2 GHz.

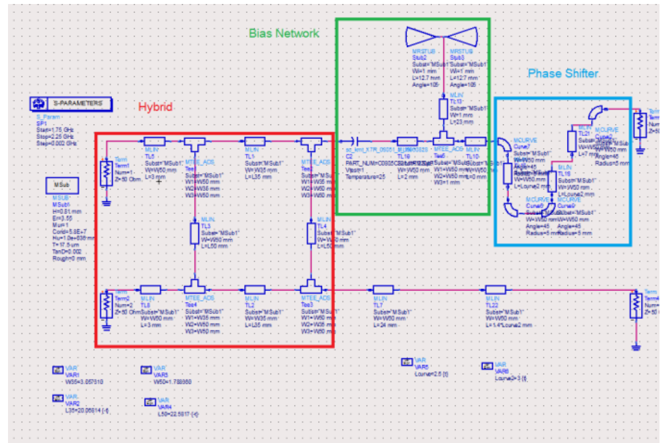

FIG. 5 (Color online). The final ADS design of the Project, whose main parts are: the hybrid (red), the bias network (Green), and the additional line delay (blue).

The purpose of the Bias network is to be able to introduce a DC voltage into one of the arms of the DD-MZM; in order to control the optical phase difference between both arms. To achieve this we have to make sure that: the DC voltage does not enter the hybrid, and that the RF current coming from the hybrid does not go towards the DC generator. The isolation of the hybrid of the 1.8V can easily be done by placing a 2.4nF capacitor just between each part of the circuit. We could have stopped the RF current from going towards the DC generator with an electromagnetic coil, but in our case the simulation of encapsulated RF inductances showed resonances due to parasitic effects close to the spectral band of interest. We then designed a DC biasing network based on $\lambda/4$ radial stubs; so that at the point of connection to the RF path in port 3: a reflection coefficient of 1 is obtained, corresponding to an open circuit impedance.

As we previously explained in the SSB test, our Mach-Zehnder had an extra 17º that we have to compensate in order to achieve the 90º phase difference we want. We had to make one of the microstrip lines longer so that those 17º are achieved. We had to take into account that both ends of the circuit needed to be aligned to be able to match the entrance of the MZM. That is why the elongation of our microstrip lines is introduced as a curve. In addition, a tuning strategy was applied to ensure that the phase difference is changed without disturbing the geometrical conformation.

The final circuit would then look like figure 6.

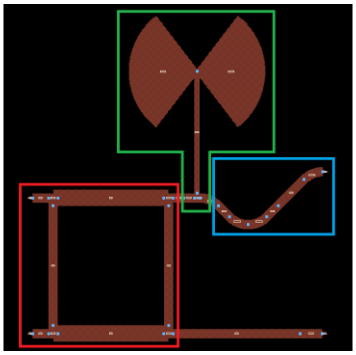

FIG. 6 The layout of the final design. The color code is the same as in FIG. 5.

V. RESULTS

The ADS software has two possible simulations available to predict the behaviour of the circuit: the electric and the electromagnetic simulations (Momentum). The main difference is that while in the first the electrical behavior of each element in the circuit is modelled through its constituent equations, in the second one we are taking into account the electromagnetic coupling between the different elements of our microwave circuit.

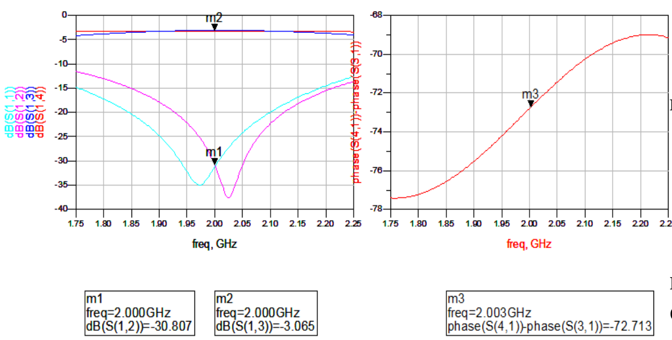

FIG. 7 (Color online). Momentum electromagnetic simulation of the final design in FIG. 5. In the left: the modulus of the transmission coefficients. In the right: the difference between the phase of the port 4 minus the phase of port 3.

As we can see in figure 7, good return loss and isolation values in excess of 35 dB are predicted at the working frequency with approximately 150 MHz band considering a 20 dB threshold. The power is equally distributed between the two exit ports (3 and 4; red and blue lines) and the relative phase difference between them is approximately -73º: which is the value required to obtain the SSB in our Fujitsu FTM7921 ER, according to the SSB Test conducted (section III).

We have confirmed that the NA measures of the circuit built are in perfect agreement with the Momentum simulations. and therefore, when used in conjunction with the DD-MZM an optical SSB should be achieved.

A modification of the experimental setup with respect to that in section III was required due to non-availability of the BOSA. We had to use a second laser, which we adjusted to have around 10 GHz frequency difference from the one used as optical source and through heterodyne mixing of the two managed to see the spectrum of the DD-MZM output in an electrical spectrum analyzer. The final result obtained when using port 1 as an input and terminating port 2 is shown in Figure 8. We observe a better than 20 dB rejection. We also confirmed that by using port 2 while terminating 1 an upper SSB with approximately the same rejection can be obtained.

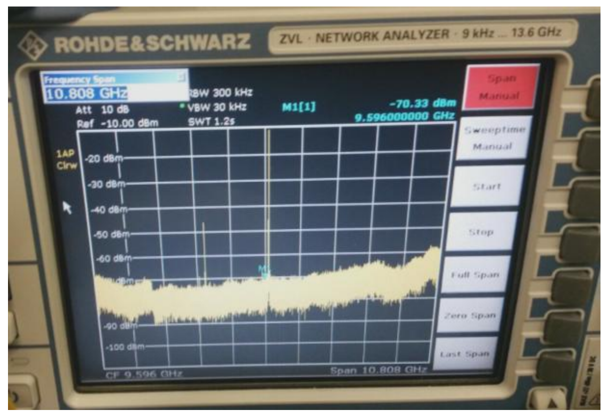

FIG. 8 (Color online).Screenshot of the electrical spectrum resulting from heterodyne mixing of the two lasers.

VI. CONCLUSIONS

We have shown how a quadrature (90°) hybrid with the required complements and adjustment of the microwave circuit when combined with a DD-MZM can yield an optical SSB modulation of a microwave signal at 2 GHz. Our experiment is in strongly agreement with our simulations: the rejection between sidebands achieved has been better than 20 dB. The procedures shown here may be used to extend operation to higher frequency bands in order to expand the range of applications.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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