Design, Simulation and Fabrication of a 5G Microwave Circuit

Alexandre Justo Miró and Joan Nigorra Barceló
Universitat Politècnica de Catalunya, Barcelona, Spain
(Dated: June 5, 2018)

Abstract: A microwave circuit aimed at obtaining Optical Single Sideband has been designed, simulated and fabricated, operating optimally at 5G frequencies, namely 3.6 GHz [1]. The circuit consists of a quadrature hybrid, a phase shifter and a bias network. After the circuit, the output signal is optically modulated by means of a dual-drive Mach-Zehnder modulator. Firstly, the design and simulation of the microwave circuit was made using the Advanced Design System (ADS) software. Finally, the designed circuit was physically fabricated and measured, and the results of the sideband rejection done by heterodyne spectrum measurements are shown.

I. INTRODUCTION

5G technologies are nowadays on the spot. They are expected to be in use by 2020. The vast majority of the companies are currently investing to prepare for the new mobile wireless standard and developing techniques so as to make communications more efficient. Although other frequencies will perform 5G, the most common frequency used will be that of 3.6 GHz [2].

Optical fibers provide high capacity and long reach connections to antenna sites. Radio-over-fiber techniques allow for cost reductions through simplification of the required hardware by transmitting the signal directly into the wireless format. One of the main causes of signal degradation over long distances in optical fibers is chromatic dispersion, especially for high RF carrier frequencies [3]. In order to reduce this dispersion, one of the bands of the modulated signal can be eliminated: this is called Single Sideband modulation (SSB). This type of modulation is of interest because it is applicable in different fields. In order to get a SSB, one possibility is to use a dual-drive Mach-Zehnder modulator (DD-MZM), only under certain specific conditions explained in this article.

The structure of the paper is the one that follows. Firstly, Section II consists of a theoretical explanation of how to get the SSB, followed by a description of the most relevant mathematical concepts of the hybrid quadrature and the DD-MZM as a way of achieving it. Secondly, Section III lies in the assembly carried out in order to reckon the extra phase induced by the DD-MZM. Then, Section IV is about the design process and simulation in ADS. Besides, Section V is where the experimental results of the microwave circuit are presented and compared to those obtained in the simulation. Finally, some conclusions are remarked in Section VI.

The ultimate goal is to design a microwave system using ADS that achieves the conditions of use of the MZM modulator, in order to obtain a single side band for 3.6 GHz.

II. FUNDAMENTALS BASED ON THEORY

A. Dual-drive Mach-Zehnder modulator

A Mach-Zehnder dual-drive modulator can be modeled as in Figure 1. It is needed a laser that gives a continuous wave signal with amplitude A and frequency ω_0. The continuous signal is connected to the input of this optical device. In order to obtain a single sideband optical modulation, the phase of each branch is modulated by a radio frequency signal of frequency ω_{RF} and amplitude V_{RF}. However, it has a phase difference of θ. In addition, one of the branches is biased with a direct current of amplitude V_B.

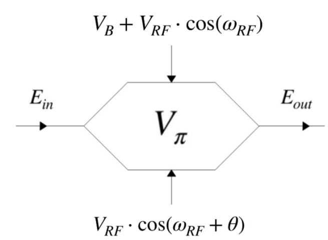

FIG. 1. Model of a dual-electrode MZM.

Following the sketch in Figure 1 with V_π the voltage for a π phase change in each of the branches of the interferometric structure. The optical field at the output of the DD-MZM is:

$$E'_{out} = \frac{E_{in}}{2}[\exp(j\frac{\pi}{V_\pi}(V_B + V_{RF}\cos(\omega_{RF}t))) + \exp(j\frac{\pi}{V_{pi}}V_{RF}\cos(\omega_{RF}t+\theta))] \tag{1}$$

By letting $\alpha = \frac{\pi}{V_\pi}V_B$, $\beta = \frac{\pi}{V_\pi}V_{RF}$ and considering that usually $V_{RF} << V_\pi$, a Taylor expansion $e^x \approx 1+x...$ may be used to get:

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

By letting $\theta = -90°$, get the following:

$$E'_{out} = E_{IN}e^{j\frac{\alpha}{2}}[\cos(\frac{\alpha}{2}) + j\frac{\beta}{2}e^{j\frac{\alpha}{2}}(\cos(\omega_{RF}t) + e^{-j\alpha}\sin(\omega_{RF}t))] \tag{3}$$

So that with $\alpha = \pm 90°$, lower and upper SSB signals are respectively obtained. Likewise, for $\theta = +90°$ and $\alpha = \pm 90°$, upper and lower SSB signals are respectively obtained.

B. Quadrature (90°) Hybrid

The quadrature Hybrid 90° (see Fig. 2) is one of the fundamental parts of the circuit. The characteristic impedance of the microstrip lines Z_0 is taken as 50Ω, because that is the typical impedance in radio frequency, and also that of the DD-MZM inputs.

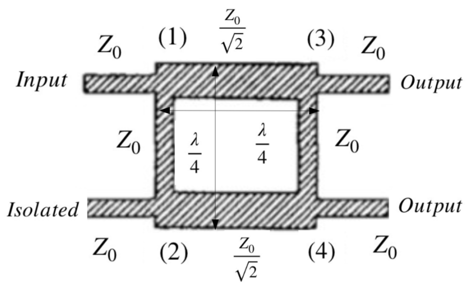

FIG. 2. Quadrature Hybrid 90° example.

The scattering matrix from the Figure 2 can be obtained by using an even-odd decomposition [4]:

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

This scattering matrix tells that if, for example, port 1 is used as an input and the rest of ports are terminated (connected to 50Ω load devices) there will be no signal at port 2, and ports 3 and 4 will get half of the power each, with a 90° phase difference of port 3 relative to port 4. If, instead, port 2 is used as input, port 1 will get no power, and ports 3 and 4 will again share half of the power, but in this case it is port 4 which has a 90° relative phase difference with respect to port 3. Therefore, ports 1 and 2 are said to be mutually isolated ports. By the same token, ports 3 and 4 are also mutually isolated ports. In connection with Section II.A, the idea is to exploit the property of the hybrid to readily provide two ports with a 90° relative phase difference to obtain an optical SSB modulation.

III. SSB TEST

Ideally, the quadrature hybrid gives a phase difference of ±90°, and the output signal goes into the MZM and one of the sidebands is cancelled. However, the MZM is not ideal, and it adds a certain phase shift due to the different length of its cables. Thus, ±90° are not directly achieved. The way of overcoming this problem is to measure the phase shift induced by the MZM, and substract it from the output phase shift of the microwave circuit. That is to say, after the quadrature hybrid itself, the phase shift is at ±90°, so a phase shifter just after the hybrid must be built in order to change the final phase of the whole circuit to the proper value, such that after the phase induced by the MZM, the final phase that is actually present at the modulator branches is ±90°.

In order to obtain the phase difference of 90° in the MZM radiofrequency ports, there was required a real simulation of the final assembly. For that purpose, a laboratory setup was built, consisting of a broadband power splitter that could be used between 2 GHz and 18 GHz (acting as the hybrid), a tunable phase shifter, an encapsulated bias-t network, a radio frequency signal generator, a direct current generator and a set of two lasers, each accompanied by one polarizer.

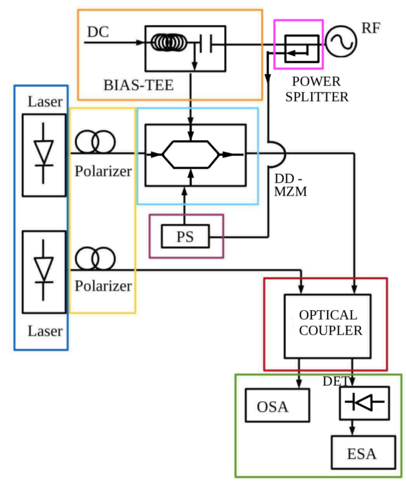

FIG. 3. Test circuit build-up. From left to right: lasers (blue), polarizers (yellow), bias network (orange), Mach-Zehnder Modulator (sky blue), phase shifter (purple), power splitter (magenta), RF signal generator (white), optical coupler (red), measurement setup (green).

In the following, the setup in Figure 3 and the course of the test are explained. First of all, the laser source was set at 5 dBm and 1550 nm wavelength. This laser is connected to the input of the Fujitsu DD-MZM. It is necessary to emphasize the use of the two polarization controllers used just after the lasers, since this way the laser beams enter with maximum power in the setup. Then, the 3.6 GHz radio frequency signal is connected to the hybrid input. Next, connected to the power splitter, there are both the bias-t network and the electronic phase shifter. Both the output of the power splitter and the second laser were connected to each one of the inputs of the DD-MZM. Finally, the setup ends with the connection of the DD-MZM output to the OSA in order to see the spectrum of the modulated optical signal.

When the setup was working, two peaks of optical power appeared on the OSA, each one corresponding to each laser. By changing the wavelength of one of the lasers, it was possible to adjust those two peaks and get to see only one. Then, by means of a photodetector, two peaks appeared on the oscilloscope again with higher resolution. Specifically, by doing the FFT of the signal, there was a carrier signal accompanied by two sidebands, one on each side. Then, with the help of the tunable phase shifter, it was found the desired phase shift such that one of the sidebands was eliminated.

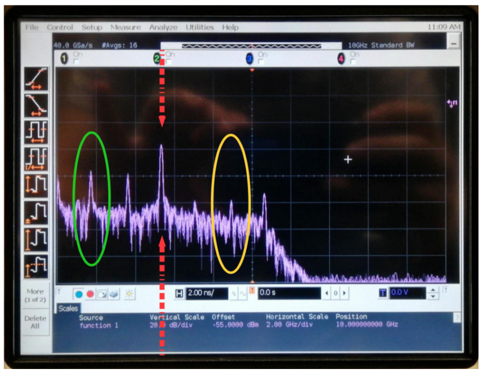

FIG. 4. FFT of the signal corresponding to the test. Cancellation of one side band. In red, the carrier signal. In green, one side band. In yellow, side band cancellation.

The final step was to take the setup formed by the power splitter, bias-t network and phase shifter, and bring it to the vectorial network analyzer (VNA), so as to measure exactly what phase difference was obtained between the lines after the bias and the phase shifter. This was performed by entering a 3.6 GHz signal through the hybrid and first exiting through the bias branch and placing a 50Ω load on the phase shifter branch, and vice versa.

The results of the aforementioned measures were -54.434° and 5.866° respectively. So, after performing a simple subtraction, the relative phase difference turns out to be about -60.3°. This is definitely the phase difference desired at the outputs of the microwave circuit.

IV. ADS SIMULATION

Once the data about the circuit was collected, it was time to design it in ADS. The first step is the design of the hybrid, then the bias, after that the phase shifter, and finally, the samplings of the whole circuit and the electromagnetic simulations of the whole.

The substrate used corresponds to Rogers 4003. LineCalc was used to adjust the widths and lengths of the microstrip lines to ensure the desired impedance and electrical lengths at 3.6 GHz. Therefore, there was needed a -60.3° phase difference in the output. Furthermore, a physical distance of 30.5 mm between the output ports was mandatory, since they must be connected directly to the Mach-Zehnder modulator, whose distance between connectors is 30.5 mm.

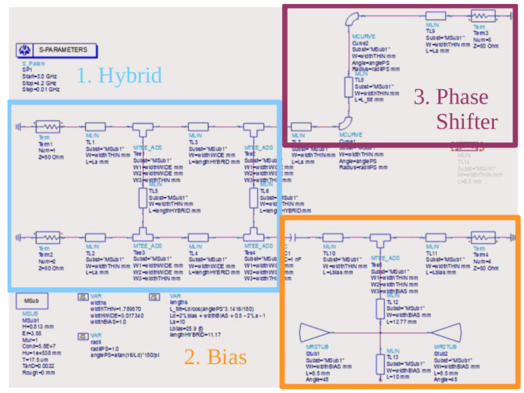

FIG. 5. Schematic of the circuit designed with ADS software.

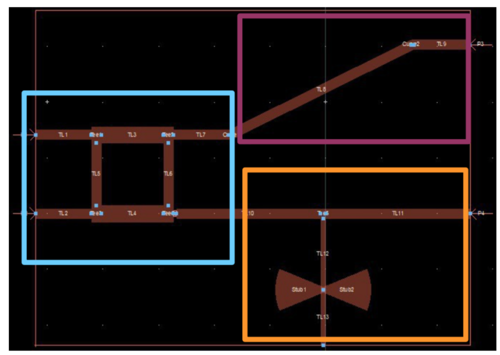

FIG. 6. Final layout of the circuit in ADS software.

The purpose of the bias network is to introduce a direct current voltage into one of the arms of the MZM, in order to control the optical phase difference between both arms. To achieve this, it is important to make sure that the direct current voltage does not enter the hybrid, and that the radio frequency current coming from the hybrid does not enter the direct current generator. The isolation of the hybrid of the $2.4V$ can be done by placing a $850pF$ capacitor separating each of these two parts of the circuit. For this purpose, it was designed a direct current biasing network, whose parameters were tuned such that at the point of connection to the radio frequency path in port 3 a reflection coefficient of 1 is obtained, corresponding to an open circuit impedance.

The third part of the design consists of achieving the necessary electrical gap between ports 3 and 4. So, from the output 4 of the hybrid, there are -90°, but -60.3° are desired at the end of the circuit. So, there was needed to add 29.7° in order to achieve the desired -60.3°. This is achieved by making one microstrip line longer than the other. There were several options to tackle this. However, as it can be seen in Figure 6, with just a diagonal line with the proper length it was enough. During the design process, it was important to take into account the problems of adaptation and interferences between lines. Both ends of the circuit needed to be aligned to be able to physically match the entrance of the Mach-Zehnder modulator. In addition, a tuning strategy was performed to ensure that the phase difference is changed without disturbing the geometrical conformation.

V. RESULTS

The ADS software offers two possible simulations. Those are the electric one and the electromagnetic one (Momentum).

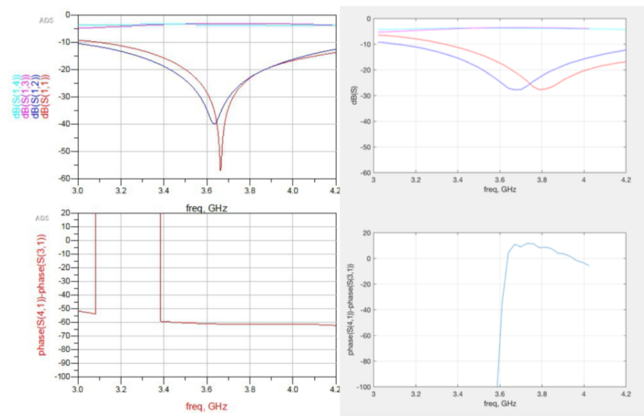

FIG. 7. S parameters and phase shift: simulated (left) vs. measured (right).

In the first one, the electrical behavior of each element in the circuit is modelled through its constituent equations, in the second one they take into account the electromagnetic coupling between the different elements of the circuit.

As it can be seen in Figure 7, good return loss and isolation values below 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; magenta and cyan curves respectively) and the relative phase difference between them is approximately -60.3°, which is the value required to obtain the SSB in the Fujitsu FTM7921 ER according to Section III.

It has been confirmed that the measures of the circuit fabricated are in agreement with the Momentum simulations. Therefore, when the fabricated circuit is used in conjunction with the DD-MZM, an optical SSB is achieved.

FIG. 8. FFT of the signal corresponding to the fabricated circuit. Proof of the one sideband cancellation at 3.6 GHz.

In order to perform heterodyne, a second laser was adjusted at around 10 GHz frequency difference from the one used as optical source. Through heterodyne mixing of the two, it was possible 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. There is a better than 20 dB rejection.

VI. CONCLUSIONS

A quadrature 90° hybrid with the convenient complements and correctly tuned, when combined with a DD-MZM, can yield an optical SSB modulation of a microwave signal at the 5G frequency, 3.6 GHz. The experiment is in strongly agreement with the simulations: the achieved attenuation between sidebands is below 20 dB.

VII. ACKNOWLEDGEMENTS

The authors are glad to thank the tutor of this project, María Concepción Santos Blanco, from the Signal Theory and Communication Department of the Universitat Politècnica de Catalunya; and Daniel Nuño Gómez, PhD Student; for their invaluable help along the process.

[1] *ADSL Zone* `https://www.adslzone.net/2018/02/14/bandas-frecuencia-5g-europa/`

[2] *Plan Nacional 5G 2018-2020*, Secretaría de Estado para la Sociedad de la Información `http://www.minetad.gob.es/telecomunicaciones/5G/Documents/plan_nacional_5g.pdf`

[3] GOVIND P. AGRAWAL, *Nonlinear Fiber Optics*, 5^{th} Edition, 2013.

[4] JAVIER BARÁ TEMES, *Circuitos de microondas con líneas de transmisión*, Edicions UPC, 1^{st} Edition, September 1994.

[5] DAVID M. POZAR, *Microwave Engineering*, 4^{th} Edition, December 2011.