Photonic RF Frequency Measurement Combining SSB-SC Modulation and Birefringence

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Abstract: A new technique to RF instantaneous frequency and amplitude measurement is presented and experimentally demonstrated. The architecture described is based on a single sideband modulation with suppressed carrier (SSB-SC) and the measurement of the Stokes parameters at the output of a birefringent medium. The results obtained show errors below 50 MHz in the 59 % of measurements carried out in a range from 1 to 11 GHz and an average power error of 0.34 dB. The technique shows the potential to increase the resolution and the range by increasing the differential time delay of the birefringent medium.

Keywords: *Frequency measurement, microwave photonics, optical microwave processing.*

1. INTRODUCTION

In fields such as radar warning receivers, electronic warfare and microwave instrumentation, the instantaneous frequency measurement of a radio frequency signal (RF) is of great interest. Conventional electronic systems used to carry out this kind of measurement can provide high resolution results however it is difficult to achieve both instantaneous and broadband measurements. Moreover these devices usually show disadvantages like large size, high power consumption, susceptibility to electromagnetic interference, etc. For these reasons the implementation of instantaneous frequency measurement systems (IFM) by means of photonic techniques [1] has attracted the interest of several research groups since they are an interesting alternative to their electronic counterparts.

Different photonic architectures have been proposed so far [2-11] using a variety of physical phenomena and implementations such as chromatic dispersion [2-3], two cascaded Mach-Zehnder modulators [4-5], optical filters [6-7] diffractive gratings [8], polarization-based interferometer [9] phase modulators and dual-output modulator [10-12], to cite some examples. All techniques presented are aimed at improving some of the following features: range, resolution, possibility of providing RF power measurement, reduction of the system complexity. Unfortunately, no approach covers every feature.

An alternative to the implementation of RF instantaneous frequency measurement was presented in [13]. In this paper we elaborate on that to show that this approach can be used to simultaneous measure the power and frequency of a RF signal. Moreover a new approach with improved range and resolution is proposed.

2. PRINCIPLE OF OPERATION

The basis of the technique proposed in this paper is the measurement of the state of polarization of the RF signal under test at the output of a birefringent medium, from which the RF frequency will be derived.

Birefringent materials have a pair of principal states of polarization (SOP) around which the SOP at the output rotates describing a circumference in the Pointcaré sphere when the wavelength changes. Depending on the orientation of the beam at the input of the medium, different circumferences are described, all of them centred around one of the Poincaré sphere diameters, as seen in Fig. 1. Therefore, if the differential group delay (τ) of the medium is known, it is possible to determine the frequency shift from the change in the Stokes parameters of the polarization output as given by [14]:

$$\Delta f = \frac{\Delta \theta}{2\pi\tau} \qquad (1)$$

where Δf is the incremental change in optical frequency and Δθ is the radian angle of the arc (Fig. 2). Thus, frequency shifts can be measured from the angle of the arc described by the Stokes parameters around the principal SOP. In addition, the electrical power of the RF signal can be measured from the Stokes parameter S_0 since it provides the optical power of the beam.

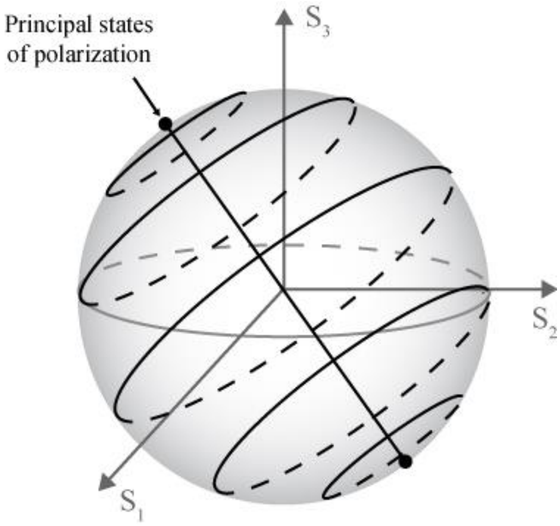


Fig. 1.- Circumferences described on the Poincaré sphere by the SOP of an optical signal at the output of a birefringent medium. Each circumference corresponds to a particular orientation of the beam at the input of the medium.

Given a reference point, obtained from a known frequency, and using (1) it is possible to unambiguously determine the frequency of the signal under test. In light of (1) it can be seen that the range wherein a frequency can be determined depends on τ,

$$\Delta f = \frac{1}{\tau} \qquad (2)$$

i.e, the smaller τ the larger the frequency range. However, a larger τ means a better resolution. Using a larger τ, a frequency shift of the microwave signal under test translates in a wider Δθ. Given that the resolution in the measurement of the Stokes parameters is the same, the resolution in the measurement of the frequency is improved when a larger τ is used.

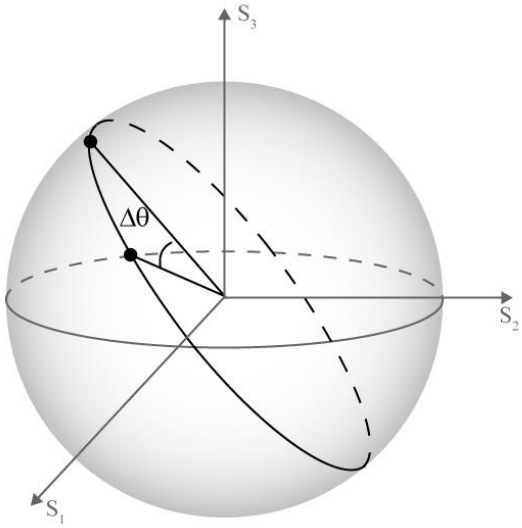


Fig. 2.- Arc described by an optical signal on the Poincaré sphere when its frequency is changed.

Additionally, the resolution in the measurement depends on the circumference described. In particular, the maximum resolution is achieved when the centre of the circumference matches the centre of the Poincaré sphere, i.e., when the optical signal is launched at 45º to the birefringent medium axis, as a result, the radius of the circumference is maximum.

In Fig 3 the block diagram of the proposed technique is depicted. A CW laser is amplitude modulated by a dual parallel MZM to generate a single sideband modulation with suppressed carrier (SSB-SC) in order to measured de Stokes parameters of the sideband at the output of the birefringent medium, since the optical frequency of the sideband depends linearly on the RF frequency. Next, a polarizer, set at an angle of 45º to the birefringent medium axis, is used to increase the frequency resolution, ensuring that the circumference described in the Poincaré sphere is maximum, as well as to avoid errors caused by changes on the optical signal polarization. After that, the beam is launched to a birefringent medium and the Stokes parameters measured by means of a polarimeter. Finally, the results are processed to obtain the RF frequency.

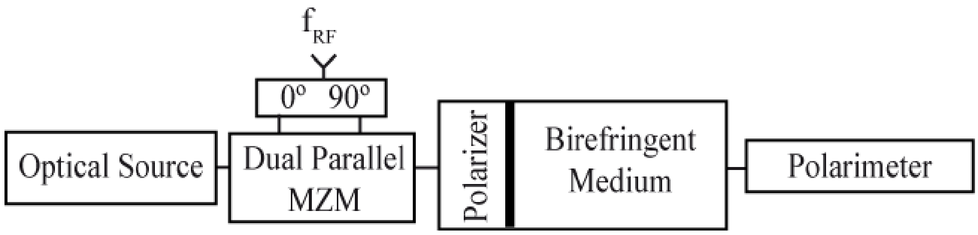


Fig. 3.- Schematic diagram of the technique proposed.

Taking into account the expressions for a dual parallel MZM [15] the relation between the electrical power and the optical power can be derived as follows. The amplitude modulated optical field at the output of the dual drive MZM can be expressed in terms of Bessel function of the first kind as:

$$\vec{E}_{opt}(t) \propto J_1\left(\frac{\pi V_{RF}}{V_\pi}\right) e^{-i(\omega \pm \omega_{RF})t} \tag{3}$$

where ω and ω_{RF} are the angular frequency of the optical carrier and the RF signal, respectively, V_{RF} is the amplitude of modulating signal and V_π is the MZM switching voltage. If the ratio ($\pi V_{RF}/V_\pi$) is small, only the first-order sideband is generated and equation (3) can be simplified as:

$$\vec{E}_{opt}(t) \propto \frac{\pi V_{RF}}{V_\pi}\ e^{-i(\omega \pm \omega_{RF})t}. \tag{4}$$

As a result, the amplitude of the modulating signal is proportional to the amplitude of the sideband generated.

Since the technique presented in this paper is based on the measurement of the SOP of the sideband, amplitude fluctuations of the optical carrier do not affect the results obtained.

On the other side, the measurement error is limited mainly by two error sources. The first one comes from the wavelength drift of the optical source which leads to a change in the SOP of the sideband. However cooled stable optical sources are widely available. The second error source comes from the SSB-SC modulation. If the SSB-SC is not properly achieved a second SOP is generated, due to the optical carrier, which leads to an error in the SOP measured by the Stokes Parameters. On the other side, high RF input powers could lead to an increase of the nonlinear terms, however this problem can be mitigated by one of an external modulator linearization technique proposed in the literature [16].

The error source coming from the SSB-SC modulation can be estimate by the Jones formalism. The polarization of light can be represented as

$$P = \frac{1}{\sqrt{E_x{}^2 + E_y{}^2}} \begin{pmatrix} E_x \\ E_y e^{i\theta} \end{pmatrix} \tag{5}$$

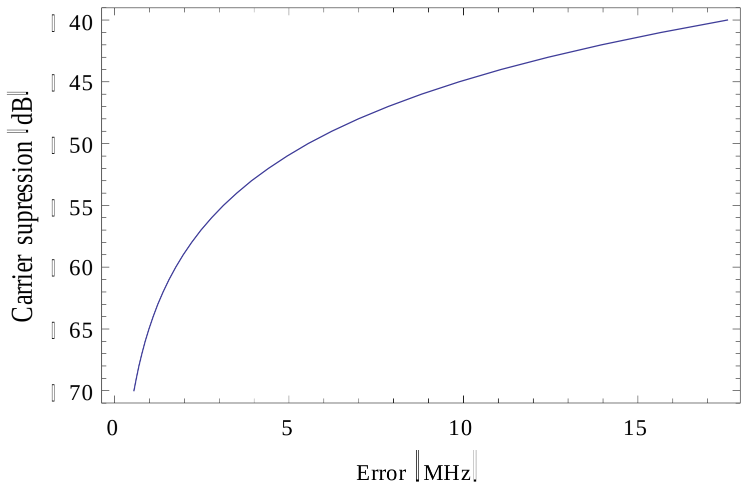
where φ is the phase difference between components of the light. Therefore at the output of the DGD the state of polarization can be expressed as

$$P \propto \begin{pmatrix} E_x^s (1+m) \\ E_y^s (e^{i\theta_s} + e^{i\theta_c} m) \end{pmatrix} \tag{6}$$

where $E_{x,y}^s$ are the x-component and the y-component of the sideband, θ_s and θ_c are the phase difference between components of the sideband and the optical carrier, respectively, and m is defined as the suppression carrier index being equal to 0 when the optical carrier is totally suppressed. As a result, the phase difference between components of the light at the output of the DGD can be expressed as:

$$\theta = ArcTan\left[\frac{mSin(\theta_c) + Sin(\theta_s)}{mCos(\theta_c) + Cos(\theta_s)}\right] \tag{7}$$

From this equation the error in the measurement of the sideband frequency coming from the SSB-SC modulation the can be calculated.



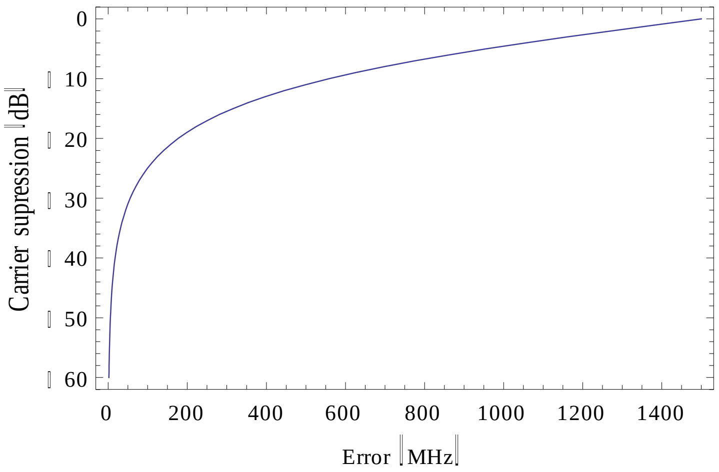


Figure xxx shows the error in the measure of a 3 GHz tone with a τ of 90 ps and an optical carrier of 1550nm. As can be seen, this error is below xxx MHz for values of carrier suppression better than xx dB.

Finally it has to be pointed out that a system with both large range and precision could be implemented by means of the combination of two differential group delay modules with different τ (Fig. 4). In this way, the first birrefringent medium would provide a course measurement and the second one a fine result.

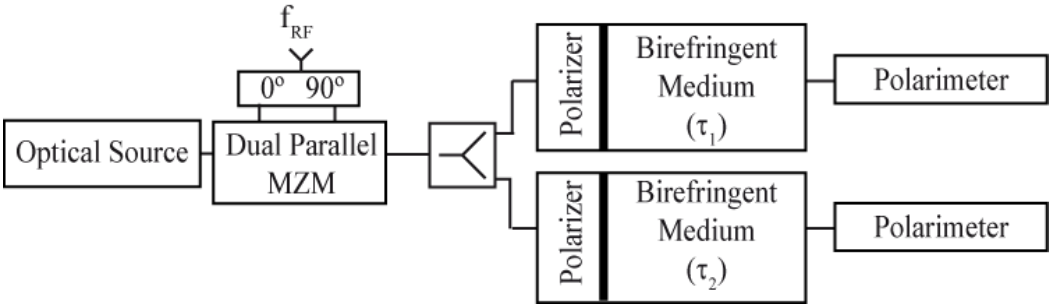


Fig. 4.- Schematic diagram combining two differential group delay modules.

3. EXPERIMENTAL SETUP

The photonic IFM scheme shown in Fig. 5 was employed to validate the proposed approach which provides RF amplitude and frequency measurements and compared them with the results obtained by a commercial spectrum analyzer. First, a distributed feed back laser (DFB) at 1550 nm with an output power of 9 dBm was launched to a dual drive MZM (up to 10 GHz) fed by the signal generated by a microwave oscillator. Next, the signal was launched to a polarizer and a differential group delay module with an incorporated polarizer at 45º. After that, the different RF frequency inputs were measured from the Stokes parameters by means of a polarimeter and a LabView interface developed for this purpose. Simultaneously, the RF signal generated was measured by a spectrum analyzer. Note that, polarization controllers were used to provide the correct state of polarization to the MZM and the polarizer in order to maximize the optical power of the system.

The first measurements performed were intended to demonstrate that resolution improves with larger τ. For this purpose, the RF frequency of a 6 GHz tone was measured 2000 times with different group delay modules, i.e, different τ, in particular 10 and 90 ps. From the normalized histograms obtained (Fig. 6) it can be seen that larger τ means a better resolution since for a τ equal to 90 ps the results show errors around 11 MHz whereas using τ equal to 10 ps the errors are around 97 MHz.

Next, using a differential group delay module of 90 ps, some measurements were carried out changing the RF input and compared with the results provided by the spectrum analyzer. In order to compare both sets of measurements, a linear fit was done. As can be seen in Fig. 7, the correlation coefficient (R^2 = 0.9999) indicates that our results agree quite well with the measurements obtained using the commercial device showing the capability of the proposal to implement an IFM system.

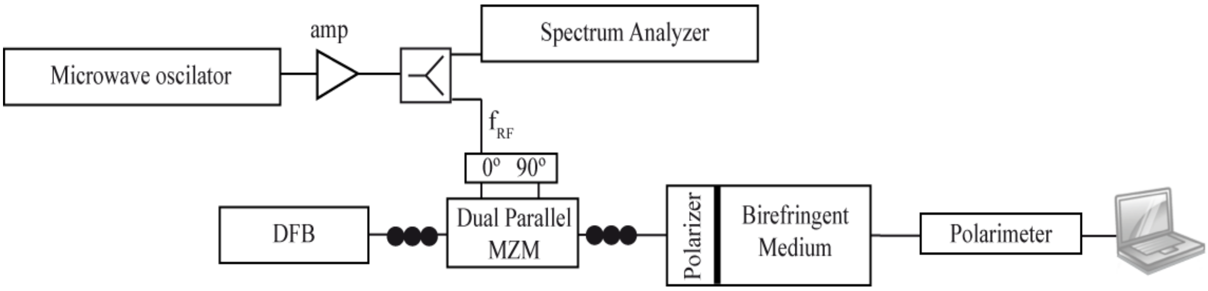
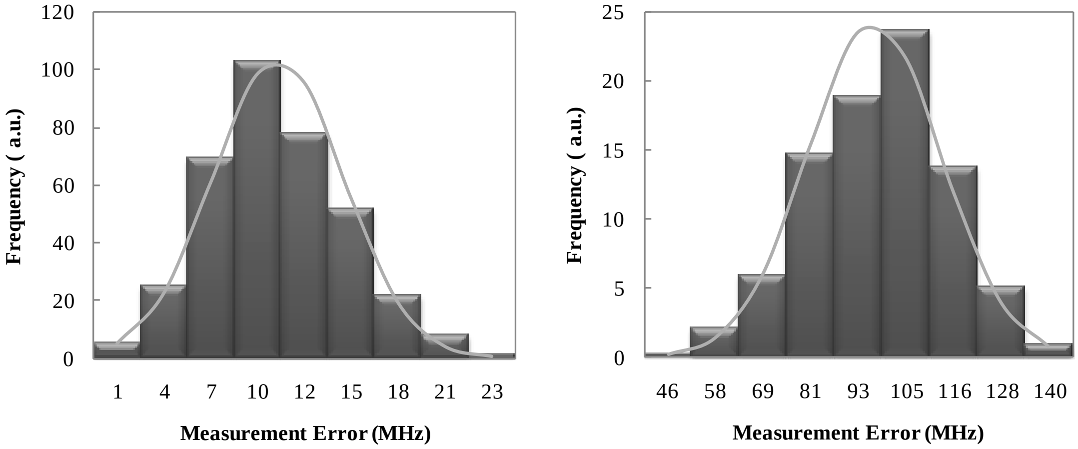


Fig. 5.- Experimental setup to proof the concept.

The measurements showed an error below 50 MHz in 59% of the points which was mainly limited by the measurement accuracy of the τ value.

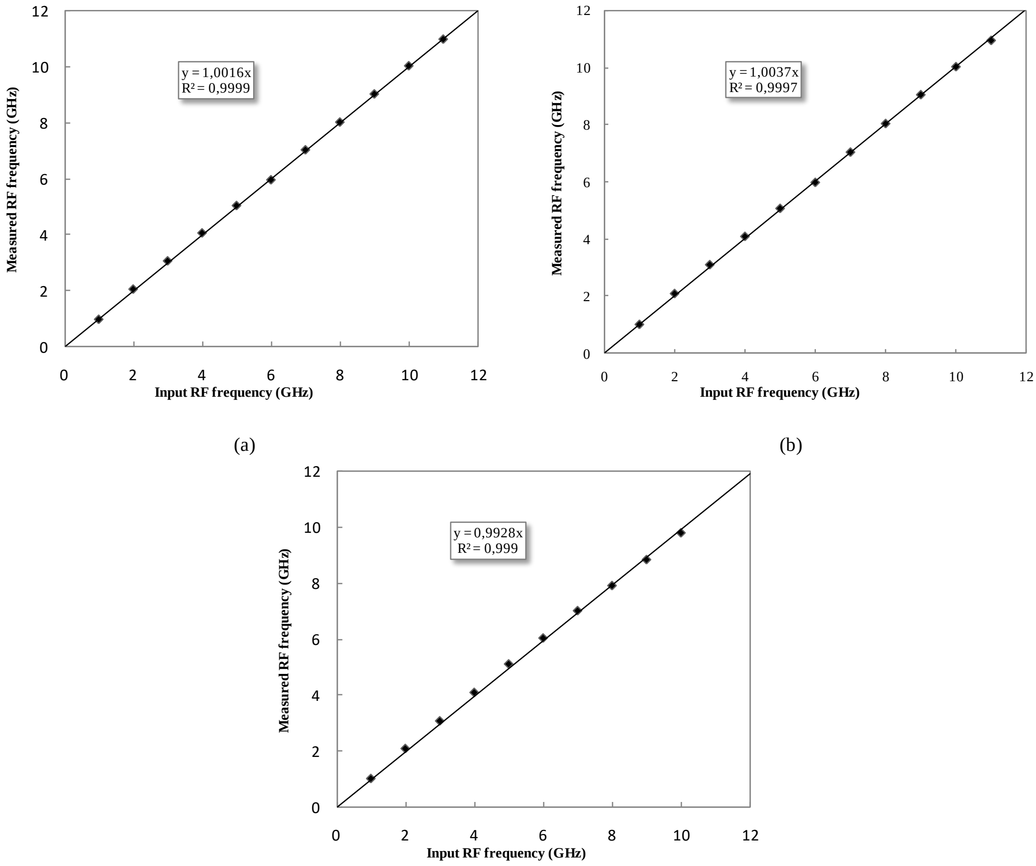
The measurements were carried out up to 11 GHz. The differential group delay module used which showed a τ equal to 90 ps and therefore the measurement range was from 0 to 11 GHz, approximately. As it said in the previous section, this measurement range can be increased by the use of a smaller τ. On the other side, accuracy can be increased by a better characterization of the τ value as well as the use of a larger τ.

Finally, the capability to measure the RF power from equation (4) was demonstrated. As in previous measurements the results obtained were compared with the results provided by the commercial device showing a good correspondence as can be seen in Fig. 8 with an average error of 0.34 dB. As a result the system allows the measurement of the RF amplitude from the amplitude of the sideband generated.



(a) (b)

Fig. 6.- Normalized histograms obtained: (a) τ equal to 90 ps, (b) τ equal to 10 ps.



(a) (b)

(c)

Fig. 7.- Comparison of the RF frequency measurements carried out from the Stokes parameters and a commercial spectrum analyzer for a RF power of : (a)15 dBm, (b) 10 dBm, (c) 5 dBm.

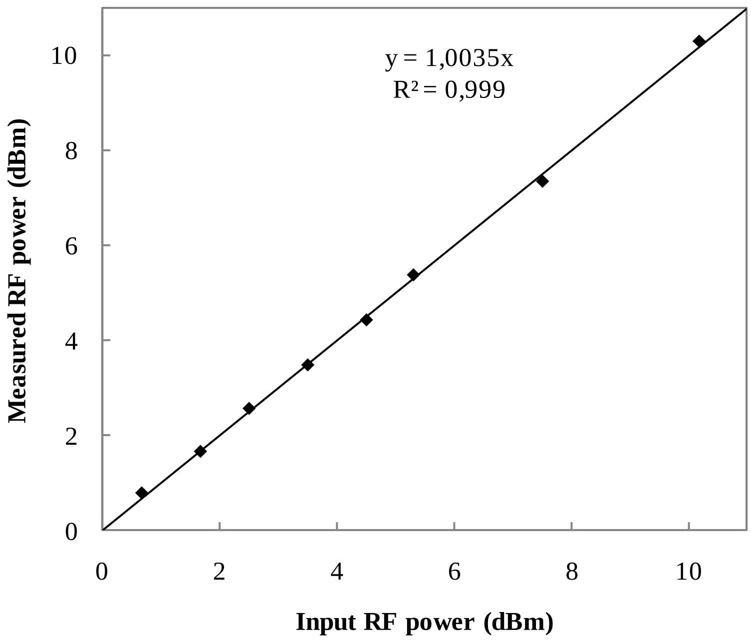


Fig. 8.- Comparison of the RF amplitude measurements carried out from the Stokes parameters and a commercial spectrum analyzer at 5 GHz

4. CONCLUSION

In this work an alternative technique for the RF frequency and amplitude simultaneous measurements has been presented and experimentally demonstrated for a frequency range from 1 to 11 GHz. Unlike previous proposals, this system is based on deriving the RF frequency from the evolution of the Stokes parameters at the output of a birefringent medium which reduces the complexity of the system whereas the frequency range of the system is increased. On the other side, the technique shows a frequency error below 50 MHz for the

59% and an average power error of 0.34 dB. Moreover, the measurements are independent of amplitude fluctuations of the optical source. In addition, the technique has potential to increase the resolution and the range by increasing the differential time delay of the birefringent medium.

Acknowledgements

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