Reflected Power Measurement of Antennas between 0 and 4 GHz using Optical Mixing of Distributed Feedback Lasers

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Abstract. *Reflected power measurement of antennas by using an alternative microwave photonic system is presented in this paper. The proposed experimental setup is based on optical mixing of two distributed feedback (DFB) lasers, where combined beams are detected by a photodetector. The resulting photocurrent corresponds to a microwave signal which is continuously tuned on bandwidths from 0 to 4 GHz. The obtained swept frequency is applied to an antenna in order to measure its reflected power. Error sources that limit the measurement accuracy of optical mixing such as effect of power deviation in the linewidth of the beat signal and errors introduced by extra fixture are studied. Results of the measurements obtained with the proposed photonic technique are calibrated and compared with traditional electrical measurements. The most important motivation on the use of the proposed technique in this paper lies in that with a simple configuration we were able to characterize microwave devices in a very wide frequency range, avoiding the use of a vector network analyzer (VNA), and thus, a complicated and tedious calibration procedure, contributing to the field of instrumentation and characterization by using photonic techniques.*

Keywords

Antenna measurement, optical mixing, distributed feedback lasers, photodetectors, optoelectronics.

1. Introduction

Currently, band-pass microwave systems such as ultra-wideband antennas are traditionally characterized in the frequency-domain through a VNA in an anechoic chamber. It is well known that VNAs have become standard tools in indoor antenna-pattern and reflected power measurements systems, which are based on measuring the transmission coefficient at a given frequency [1], having the flexibility of choosing the type of radiofrequency (RF) source that can be used. Furthermore, the accuracy of the measurement is rather intolerant to the imperfections in the calibration process. A recent study proved that antennas can be accurately measured in the time-domain using a step-function time-domain reflectometer (TDR), without the need of an anechoic chamber [2]. However the use of an impulse generator in place of the step generator in a TDR set-up has the advantage that more energy is available beyond a given frequency. In this same study the spectra measured for both systems showed that the energy in the impulse TDR reflection exceeds to the energy in the step TDR reflection approximately 4 dBV at 3.1 GHz, 6 dBV at 6 GHz and 10 dBV at 8.2 GHz when it was used a 23 ps impulse TDR compared with a 40 ps step TDR. On the other hand, with the rapid development of optoelectronic devices, the bandwidth of photo-detectors has reached several tens of gigahertz, and accurate wideband characterization of band-pass microwave systems becomes attractive by using microwave photonic techniques. The use of microwave photonic techniques in antenna measurement systems opens a technological alternative of reaching microwave signals well above of the standard instrumentation as a microwave signal generators, scalar network analyzers (SNA) or VNA. Among the methods that could be used to measure the reflected power of antennas there are those commonly used in the characterization of the frequency response of photo-detectors such as: swept frequency method [3], [4], pulse spectrum analysis

[5], interferometric FM sideband method [6], high extinction ratio optical modulator [7] and optical heterodyne method [8]. On the other hand, it is well known that with the fast development of wavelength tunable lasers the complexity of optical mixing measurement system is decreased and allows the method to be implemented easily. An advantage of this method is that measurement system could use a low-speed optical source, allowing for a straightforward measurement in the frequency response of photo-detectors and consequently the reflected power of antennas under test. Another advantage of this technique is that it does not need any high-speed light modulation source; also, it is accurate and easy to carry out. The unique limitation is the electrical bandwidth of the photo-detector (PD) used. Recently optical mixing was used by the authors to measure the reflected power of antennas in the frequency range of 0–3 GHz [9]. However it was observed that variations of output optical power cause a change in the linewidth of the beat signal, introducing errors into the reflected power in the optical measurement. Now as an additional contribution to the article previously published in [9], the authors have extended the results of the measurements to 4 GHz. Furthermore we have used a calibration method in order to remove the errors introduced by the fixture and the laser output fluctuations.

2. Theoretical Description

2.1 Study of Laser Electrical Field

The wave front of a DFB laser source can be represented by its electric field

$$E(t) = E_0(1+V(T))\exp\left[i(2\pi\nu_0 t+\varphi(t))\right] \quad (1)$$

where E_0, ν_0 are the nominal amplitude and frequency respectively; $V(t)$ and $\varphi(t)$ represent the amplitude and phase of the noise, respectively. Such a quasisinusoidal signal has an instantaneous frequency defined as [10]

$$\nu(t) = \frac{1}{2\pi}\frac{1}{dt}(2\pi\nu_0 t+\varphi(t)) = \nu_0 + \frac{1}{2\pi}\frac{d\varphi(t)}{dt}. \quad (2)$$

Supposing the variation of the noise being slow compared to the pulsation of the field $\omega_0 = 2\pi\nu_0$, and also considering that these parameters are not correlated, the autocorrelation function of the field $E(t)$ is defined as [11]

$$C_{\mathrm{E}}(\tau) = E_0^2\left[1+C_{\mathrm{V}}(\tau)\right]\exp(\mathrm{i}\,\omega_0\tau)\exp\left(C_\varphi(\tau)-C_\varphi(0)\right). \quad (3)$$

From (3), $C_V(\tau)$ and $C_\varphi(\tau)$ are the autocorrelation functions associated with the amplitude and phase of the noise respectively.

On the other hand, the power spectral density measured by an optical spectrum analyzer is related to the autocorrelation function of the field $E(t)$ by [10]

$$S_{\mathrm{E}}(\nu) = \int_{-\infty}^{\infty} C_{\mathrm{E}}(\tau)\exp(-\mathrm{i}\,2\pi\nu\tau)d\tau\,. \quad (4)$$

In a DFB laser, the power spectrum $S_{\mathrm{E}}(\nu)$ has a Lorentzian line shape with a full width at the half maximum (FWHM) of $\Delta\nu$ as written by [12]

$$S_E(\nu) = \frac{\Delta\nu}{2\pi(\nu-\nu_o)^2+\left(\frac{\Delta\nu}{2}\right)^2}. \quad (5)$$

2.2 Optical Mixing

The mixed optical intensity $I(t)$ of two single frequency laser beams with a frequency difference $\nu_b = |\nu_1-\nu_2|$ is given by [13]

$$I(t) = I_1 + I_2 + 2\cos(\varphi)\sqrt{I_1 I_2}\cos(\nu_b t) \quad (6)$$

where I_1 and I_2 are the received optical intensities, φ is the angle between polarized directions of the two beams. The photocurrent $i_c(t)$, therefore, is written as [13]

$$i_c(t) = \frac{e\eta}{h\nu}\left\{I_1 + I_2 + 2F(\nu_b)cos(\varphi)\sqrt{I_1 I_2}\,cos(\nu_b t)\right\} \quad (7)$$

where e is the electron charge, η is the quantum efficiency, $h\nu$ is the photon energy, and $F(\nu_b)$ represents the frequency response of PD. The last term in (7) corresponds to the beat signal with a frequency of ν_b, usually this term is called intermediate frequency (IF) and represents the microwave signal. The power of the beat signal can be expressed as follows [13]

$$P(\nu_b) = \left[i_{\nu b}\right]_{rms}^2 R_s \quad (8)$$

where $R_s = 50\ \Omega$ is the input impedance of the frequency spectrum analyzer. $\left[i_{\nu b}\right]_{rms}$ is the mean square root of the beat frequency photocurrent which is given by [13]

$$\left[i_{\nu b}\right]_{\mathrm{rms}} = \frac{2e\eta}{\sqrt{2}h\nu}2F(\nu_b)\cos(\varphi)\sqrt{I_1 I_2}\,. \quad (9)$$

Thus, the frequency response of photo-detectors can be expressed as [12]

$$F(\nu_b) = \frac{1}{\sqrt{2}\frac{e\eta}{h\nu}\cos(\varphi)\sqrt{I_1 I_2}}\left[\frac{P(\nu_b)}{R_s}\right]^{1/2}. \quad (10)$$

From (10), it can been seen that if the output optical intensities of two lasers, I_1 and I_2, and the polarization difference φ can be kept as constants, the frequency responses $F(\nu_b)$ of the photo-detectors can be obtained by measuring the power spectrum of the beat signals $P(\nu_b)$. This optical mixing technique is usually called Spectrum Power Method (SPM). On the other hand, when the two DFB lasers output beams, with line widths of $\Delta\nu_1$ and $\Delta\nu_2$, are mixed and detected, the power spectrum of the output beat signal $S_b(\nu)$ becomes [12]

$$S_b(\nu) = \frac{\Delta\nu_1+\Delta\nu_2}{2\pi(\nu-\nu_b)^2+\left(\frac{\Delta\nu_1+\Delta\nu_2}{2}\right)^2} \quad (11)$$

where v_b is the center frequency of the beat signal. Therefore, the peak power of the beat spectrum in the spectrum analyzer can be expressed as

$$\begin{aligned} P(v_b) &= 2\left(\frac{e\eta}{hv}\right)^2 I_1 I_2 R_s \cos^2(\varphi) F^2(v_b) \\ &\times\left[\int_{vb-B/2}^{vb-B/2} \frac{\Delta v_1 + \Delta v_2}{2\pi(v-v_b)^2 + \left(\frac{\Delta v_1 + \Delta v_2}{2}\right)^2} dv\right] \\ &= 2\left(\frac{e\eta}{hv}\right)^2 I_1 I_2 R_s \cos^2(\varphi) F^2(v_b) \frac{B}{\Delta v_1 + \Delta v_2}. \end{aligned} \tag{12}$$

In (12), $B << \Delta v_1 + \Delta v_2/2$ is the resolution bandwidth of the spectrum analyzer. From (12), it follows that the peak value is inversely proportional to the beat spectral linewidth $\Delta v_1 + \Delta v_2$, and more sensitive measurements can be expected by narrowing the beat spectral linewidth. Thus, the frequency response of PD can be written as

$$F(v_b) = \frac{1}{\sqrt{2}\frac{e\eta}{hv}\cos(\varphi)\sqrt{I_1 I_2 \frac{B}{\Delta v_1 + \Delta v_2}}} \left[\frac{P(v_b)}{R_s}\right]^{1/2}. \tag{13}$$

The variations of the linewidth and lineshape cause the variation of $S_b(v)$ as described in (11). In that case, errors will be introduced into the frequency response measurement. This optical mixing technique when linewidths of Δv_1 and Δv_2 are considered in both DFB lasers is usually called Peak Power Method (PPM). According to (10), the effect of the linewidth and the lineshape on the frequency response measurement does not exist. This shows that SPM is more accurate than PPM when measuring the frequency response of the PD and by consequence the reflected power of antennas.

2.3 Effect of Power Deviations

Two error sources limit the measurement accuracy of optical mixing: First, extra fixture, such as microwave probe, bias tee, coaxial cable, etc., will degrade the measured power of the beat signal. Second, for tunable lasers, the linewidth and power fluctuation with tuning wavelength will lead to power fluctuation of the measured beat signal. Beam fluctuation in linewidth and power has been calibrated by using self-heterodyne measurement system [13], however, the network between the PD and the electrical spectrum analyzer was not considered. For an accurate characterization in the PD frequency response and our antennas, calibrations with more complete procedures were developed in [14]. In this subsection both techniques are analyzed. According to (10) the level variation of frequency response measured in decibels (dB), caused by the fluctuation of the term $\sqrt{I_1 I_2}$ can be expressed by the following equation

$$\begin{aligned} \Delta F(v_b)_{v_1,v_2} &= F(v_b)_{I_1,I_2} - F(v_b)_{I_1,I_1} \\ &= 10\log\left[K\frac{P(v_b)}{I_1 I_2}\right] - 10\log\left[K\frac{P(v_b)}{I_1 I_1}\right] \\ &= 2.5\log\left(\frac{I_1}{I_2}\right)^2 - 2.5\log\left(\frac{P_1}{P_2}\right)^2 \\ &= 0.25(P_1 - P_2)_{dB} \end{aligned} \tag{14}$$

I_1 and P_1 are the output optical intensity and power at a fixed voltage V_1, I_2 and P_2 are the optical intensity and power at tuned voltage V_2, and K is a constant. It is shown in (14) that when the optical intensity of the tuned wavelength varies from I_1 to I_2, the measured frequency response of the PD will have a variation of 0.25 $(P_1 - P_2)_{dB}$. According to (14), it was reported that the highest level variation of frequency response caused by the variation of optical power was about 0.2 dB when frequencies of the beat signal were in the range from dc to 63 GHz [13]. In addition, the optical power variations did not exceed 0.06 dB when the beat signal frequencies were within zero to 20 GHz. Therefore, the effect of the optical power fluctuation on the measurement accuracy of PD's frequency response can be neglected in a self-heterodyne measurement system. On the other hand, the power of the beat signal also is degraded as a result of the insertion of fixtures, which will cause error in PD's frequency response and by consequence the reflected power of antennas. Considering the fixture response as well as mismatches, the real beat signal power at the v_b frequency is related to the measured power as

$$P(v_b)_{real} \alpha |C_1(v_b)|^2 P(v_b)_{meas} \tag{15}$$

where $C_1(v_b)$ is the error coefficient at the frequency v_b for correcting fixture response and mismatches. Fig. 1 shows the flow graph of the measurement system, where S_{ij}^{DUT} $(i, j = 1, 2)$ are the real scattering parameters of the device, S_{ij}^{F} $(i, j = 1, 2)$ are the scattering parameters of the fixture, and Γ_E is the electrical reflection coefficient of the electrical spectrum analyzer. S_{ij}^{Total} $(i, j = 1, 2)$can be regarded as a combined network composed of two networks in series. From Fig. 1 and by considering that the reflection coefficients of the electrical spectrum analyzer is zero the $C_1(v_b)$ can be expressed by

$$\begin{aligned} C_1(v_b) &= \frac{S_{22}^{Total} S_{11}^F + S_{12}^F S_{21}^F - S_{11}^F S_{22}^F}{S_{21}^F\left(1 - S_{22}^{Total}\Gamma_E\right)} \\ &= \frac{S_{22}^{Total} S_{11}^F + S_{12}^F S_{21}^F - S_{11}^F S_{22}^F}{S_{21}^F}. \end{aligned} \tag{16}$$

Furthermore if the fixtures are well matched, $C_1(v_b)$ can be simplified as $C_1(v_b) \approx 1/S_{21}^F$. In that case the PD's frequency response can be obtained by

$$F(v_b) \alpha \sqrt{\frac{P(v_b)_{real}}{I_1 I_2 \arctan(2\pi B/\Delta v_1 + \Delta v_2)}}. \tag{17}$$

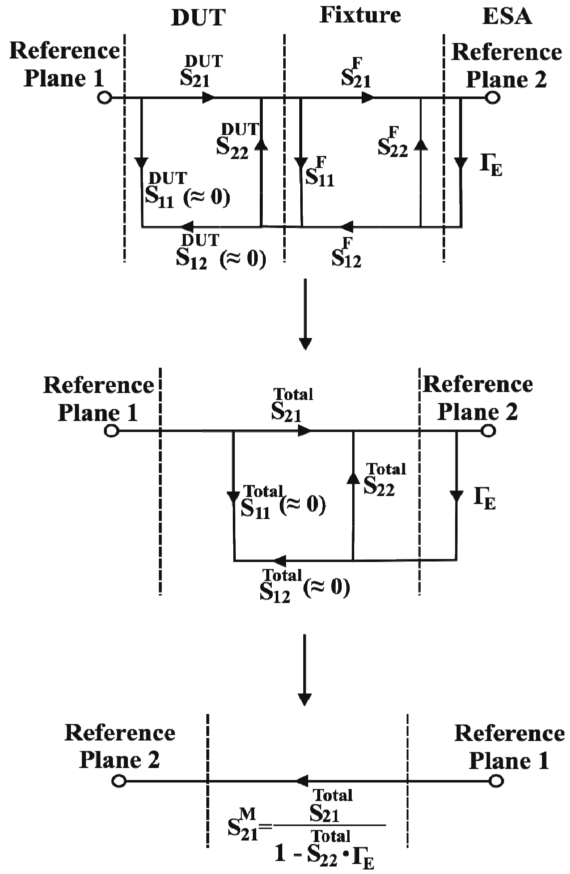

Fig. 1. The equivalent flow graph of the measurement system.

Considering extra fixture as well as laser output fluctuations, the overall calibration formula can be expressed as

$$F(v_b)\alpha\left|C_1(v_b)\right|C_2(v_b)\sqrt{P(v_b)_{meas}} \tag{18}$$

where $C_2(v_b)$ is the error coefficient at the frequency v_b for correcting laser output fluctuations of linewidth and power and can be expressed by

$$\begin{aligned} C_2(v_b) &= \frac{F(v_b)}{\left|C_1(v_b)\right|\sqrt{P(v_b)_{meas}}} \\ &= \sqrt{\frac{1}{I_1 I_2 \arctan\left(2\pi B / \Delta v_1 + \Delta v_2\right)}}. \end{aligned} \tag{19}$$

If the beat frequency can be swept continuously and the angle between the polarized directions of the two beams is kept stabilized, we can remove the errors introduced by the extra fixture as well as the laser output fluctuations using (19).

3. Experimental Results

3.1 Microwave Generation

According to the content introduced in the theoretical description, the spectrum power method to measure the beat signal power $P(v_b)$ is used in this paper. The experimental setup used for generating microwave signals is as shown in Fig. 2 of the reference [15]. In this experiment two DFB laser diodes emitting at different wavelengths are used. One of them is tunable and can be tuned over the C band with a 25 GHz channel spacing, and the other is a fiber-coupled DFB laser source with a central wavelength at 1550 nm. For microwave signal generation, the output of both lasers is coupled to optical isolators in order to avoid a feedback into the lasers and consequential instabilities to the system. A pair of polarization controllers is used to minimize the angle between the polarization directions of both optical sources. Thus, the polarization of the light issued from each optical source is matched and therefore, there is no degradation of the power levels in the microwave signals generated in the PD (MITEQ model DR-125G-A) with a typical optical to electrical transfer gain (V/W) of 1900, and –3 dB bandwidth of 12.5 GHz. The output of each controller is launched to a 3 dB coupler to combine both optical spectrums. After that, an optical output signal is received by a fast PD. The resulting photocurrent from the PD corresponds to the microwave beat signal which is analyzed with an Electrical Spectrum Analyzer (ESA; Agilent model E4407B). The other optical output resulting from an optical coupler is applied to an Optical Spectrum Analyzer (OSA; Anritsu model MS9710C) for monitoring the wavelength of the two beams. DFB laser sources provide the ability to control not only the output optical power of the fiber coupled laser diode, but also the precise temperature at which the laser is operating. Both controls can be used to tune the fiber coupled laser diode to an optimum operating point, providing a very stable output. In this way, it is observed that the wavelength of the DFB laser is shifting when its temperature is varied with a scale of 1ºC. Consequently, the beat signal frequency is continuously tuned in the bandwidth of the fast PD. For the optical mixing system used in this paper, the data acquisition rate is limited by the time required to change and to stabilize the temperature of DFB lasers. In that case and in order to guarantee a good stabilization time of the laser controlled by temperature, it was necessary to wait at least 3 minutes with the total measurements when microwave signals were captured from ESA with a resolution of 3 MHz, this being a limiting aspect when using an electric generator.

Fig. 2 illustrates the spectrums of five microwave signals generated with optical mixing technique. The generated signals are located at 1, 2, 3, 5 and 6 GHz when the temperature of the DFB laser was tuned at different values of temperatures. From this figure, we can see that the peak values of the beat signals characterize the frequency response of the PD on the bandwidth indicated above.

The spectrum powers of beat signals were measured by using the power measurement function of the ESA. Simultaneously, the peak powers of beat signals were directly recorded from the peak point by using the function “max hold”. The frequency response of the PD is obtained by recording the trace of the spectrum power or the peak power at every frequency point. As a result of the power levels that describe our PD's frequency response, this method has been used for measuring the antenna's reflected power.

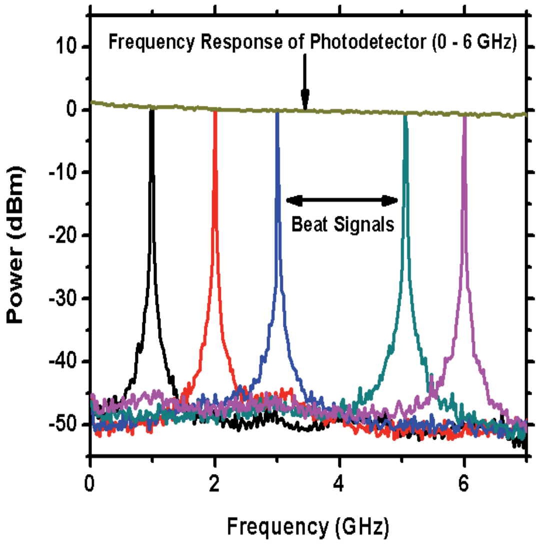

Fig. 2. Frequency response of photo-detector (0 – 6 GHz), by using optical mixing technique.

3.2 Electrical and Optical Measurements

In order to measure the reflected power of the antennas under test, it was necessary to use microwave signals on the band from 0 to 4 GHz. These frequencies are internally generated by the tracking generator of the spectrum analyzer as shown in Fig. 3. From this figure we can see that the antenna under test is connected by using a directional coupler (Mini Circuits model ZGBDC6-362HP+), allowing the reflected signal of the antenna to be measured at the reflected port of the directional coupler and simultaneously displayed on the ESA.

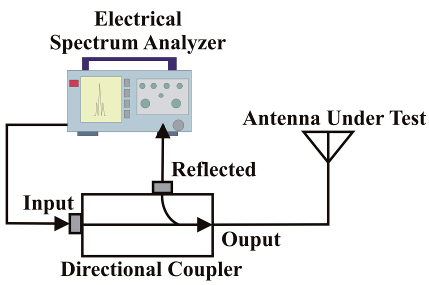

Fig. 3. Experimental setup by using a standard electrical spectrum analyzer.

On the other hand, Fig. 4 shows the experimental setup used to measure the reflected power of the antennas by using optical mixing of two DFB lasers. In this case, the PD's output was connected to the directional coupler's input port. The reflected signal of the antennas under test was measured at the reflected port of the directional coupler and displayed on the ESA. The beat frequency was swept continuously over the PD's bandwidth. In order to be consistent with previous electrical measurements, we have regarded the band from 0 to 4 GHz of our PD and the same pair of antennas. Furthermore, in the experimental setup, the angle between the polarized directions of the two beams mixed was kept constant and the errors introduced by extra fixture as well as laser output fluctuations were removed using (18).

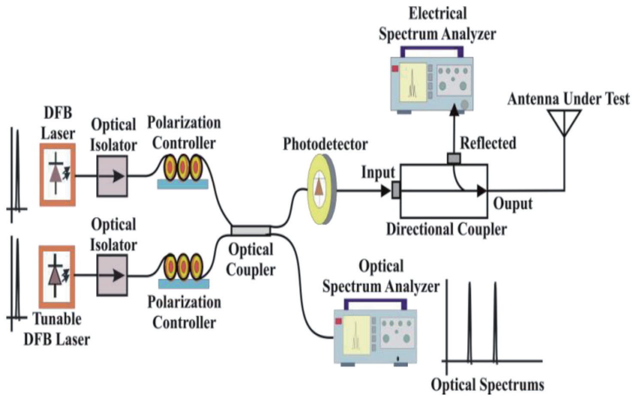

Fig. 4. Experimental setup by using optical mixing of two DFB lasers.

We have tested two different antennas which were designed to operate between 1 and 4 GHz. (Signet Instruments, antenna type S10 Dipole L/2 and Amitec Electronics, antenna type patch inset fed). The reflected power measurements of the antennas under test by using optical mixing, calibrated method and electrical measurements are displayed simultaneously in Fig. 5(a) and Fig. 5(b).

3.3 Electrical Measurement

Fig. 5(a) allows the minimum value of -26.54 dBm in one of the antennas used in this paper to be measured at 1.25 GHz. This value corresponds to the reflected loss parameter. By considering 0 dBm as reference value it is possible to calculate the reflection coefficient as $RL(\text{dB}) = -20\log_{10}|\Gamma|$ obtaining $\Gamma = 0.047$. In this case a $VSWR$ = 1.049 was calculated according to (10) in reference [16]. Thus, we find there is a good matching between the transmitter and the antenna since almost all power was transmitted to the antenna at 1.25 GHz. On the other hand, Fig. 5(b) shows the reflected power of the second antenna used in this paper. These data indicate that the reflected loss parameter of 21.75 dB was obtained at 1.25 GHz. With this result, the reflection coefficient was $\Gamma = 0.082$ and the $VSWR = 1.178$. In this case we also see there is a good matching between the transmitter and the antenna since almost all power was transmitted to the antenna at 1.25 GHz.

3.4 Optical Mixing Measurement

The minimum value of -33.91 dBm located at 1.25 GHz on the curve shown in Fig. 5(a) corresponds to the reflected loss parameter when 0 dBm as reference value is considered. It is well known that this value allows that voltage reflection coefficient to be computed by means of $RL(\text{dB}) = -20\log_{10}|\Gamma|$ obtaining $|\Gamma| = 0.020$. From this result a $VSWR = 1.04$ was calculated. This value indicates that practically all the power was transmitted to the antenna and only a small amount of power was reflected. In other words, there is a perfect matching between the transmitter and the antenna in this frequency value (1.25 GHz). Trace in Fig. 5 (b) shows the reflected power measurements of the second antenna. We can obtain from the data that the minimum value of -22.68 dBm located at 1.25 GHz on this curve corresponds to the reflected loss parameter. Again, this value is used to compute the voltage reflection coefficient by means of $RL(\text{dB}) = -20\log_{10}|\Gamma|$ obtaining $|\Gamma| = 0.073$. With this last value we can calculate a $VSWR = 1.157$. Again, we can assert that there is a good match between the transmitter and the antenna.

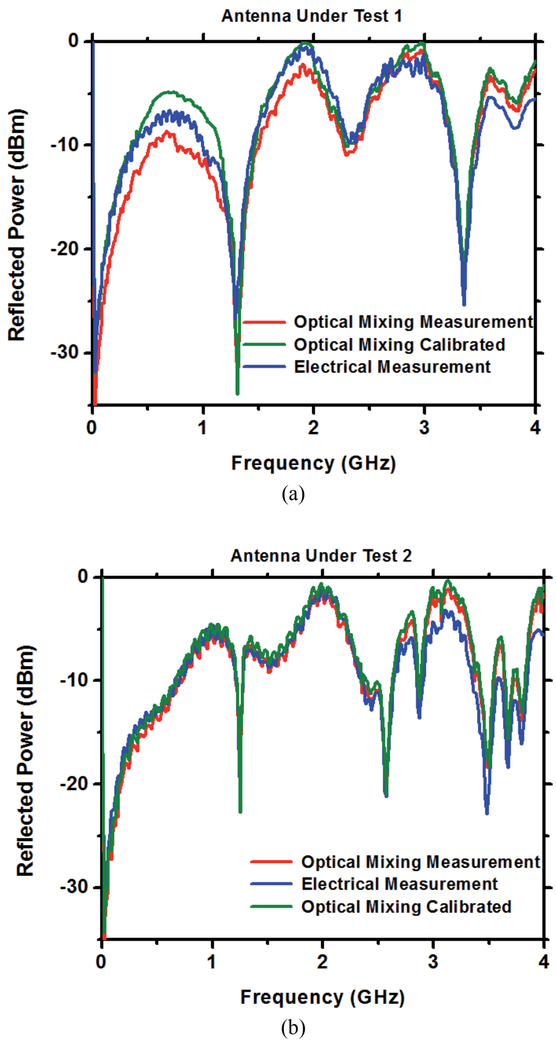

Fig. 5. Reflected power of the antennas under test by using optical mixing, calibrated method and electrical measurements.

3.5 Calibrated Method Measurement

On the other hand, in order to compare the results obtained by considering electrical and optical mixing measurement, it was necessary to include an additional trace on Fig. 5 that shows calibrated data of the reflected power measurements of the two antennas used in this paper.

From Fig. 5 we can see that optical mixing through the Spectrum Power Method allows accurate measurements of antenna systems to be done in the frequency-domain. Moreover the comparison of the results in this figure shows that optical mixing is in a good agreement with the experimental results obtained with electrical method. In addition we note that data on the band from 0 to 4 GHz indicate that the proposed calibration procedures can effectively remove the errors introduced by the fixture and the laser output fluctuations and a slight improvement in measurement accuracy has been achieved compared with only optical mixing. The proposed method can reduce the requirements in both laser output stabilities and fixture frequency performance, which is suitable to measure the reflected power of antennas in a very wide frequency range.

4. Conclusion

In this paper we have presented reflected power measurements of antennas by using optical mixing technique. With the proposed photonic method, we obtained microwave signals continuously tuned over the PD's frequency response. The antennas under test were connected to the proposed experimental setup and the reflected power was measured in the frequency range from 0 to 4 GHz. The experimental results obtained with this technique were compared to that obtained with the traditional method which uses a microwave signal that is internally generated by the tracking generator of a spectrum analyzer. We highlight the advantage of the proposed photonic technique thus avoiding a calibration procedure if a VNA is used. Results with both techniques were in good agreement. On the other hand, we have explained that because of the variations of the linewidth and lineshape of the optical spectrum output, errors can be generated in the frequency response measurement, so we proposed a calibration method in order to remove the errors introduced by the fixture and the laser output fluctuations. Good agreement between calibrated reflected power and electrical method has been achieved. The accuracy is greatly influenced by the quality of the directional coupler. In our case with directivity of 26 dB it was of 1.2 dB and can be improved by using a directional coupler with directivity > 40 dB to maintain ±1 dB uncertainty in order to be competitive with scalar vector analyzer. As proposed, the microwave photonic method is capable of generating continuously tuned microwave signals; alternatively, we can use this feature not only to measure the reflected power of antennas but also to measure the frequency response of microwave filters, microwave photonic filters and photonic devices in a wideband frequency range. The key advantage and contribution of this structure is that optical mixing of two distributed feedback lasers as an alternative method of measurement in a very wide frequency range, allows the use of a SNA to be removed. Another practical application of this technique was successfully demonstrated by the authors in [17], when a microwave signal obtained by using optical heterodyne technique was used to drive a Mach-Zehnder intensity modulator in a scheme hybrid fiber-radio. Finally, the experiment's innovative methodology allows students to have the opportunity of verifying quantitatively and deeply the reflected power measurements in the antenna's characterization, as well as hands-on experience in frequency response measurements of high-speed photo-detectors. The experiment is quite suitable for undergraduate and postgraduate optoelectronics and antennas courses.

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