The current consumption of the frequency synthesizer is 1.8 V supply voltage. The area of fully integrated synthesizers with proposed LC-VCO and AAC loop show the operation, low area, comparable FoM, and PN. The frequency synthesizer at 474 MHz frequency with combination of LO dividers. In Figure 8, the variation of PN is 2.4 dB over 1.6–2.0 V power supply and −40–85°C. The PN of the frequency synthesizer at 474 MHz is measured as −130 dBc/Hz at 1 MHz offset frequency, while the LC-VCO is operated at 948 MHz and divided by 2. The current consumption of the frequency synthesizer is 0.97 × 0.70 mm² with 180 nm CMOS process, while that of only LC-VCO is 0.40 × 0.70 mm² (Fig. 9).

4. CONCLUSION

The merits of proposed LC-VCO with DCPL are wide range of operation, low area, comparable FoM, and PN. The frequency synthesizers with proposed LC-VCO and AAC loop show the wide range of operation with low PVT variation, while covering wide operating frequency ranges of various mobile TV applications.

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Figure 9 Die photograph of Frequency synthesizer: 0.97 × 0.70 mm² (VCO only: 0.40 × 0.70 mm²)

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ABSTRACT: This article presents the characterization measurements and related uncertainty evaluation of a non-magnetic material using the Vector Network Analyzer (VNA) at microwave frequencies. The permittivity of the material under test is computed from the scattering parameters (S-parameters). The aim of the work is to highlight the different uncertainty contributions affecting the permittivity. © 2016 Wiley Periodicals, Inc. Microwave Opt Technol Lett 58:1841–1844, 2016; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29917

Key words: microwave measurements; scattering parameter measurements; relative permittivity; dielectric constant; vector network analyzer uncertainty evaluation

1. INTRODUCTION

The measurements of dielectric properties of materials at radio frequency have gained importance in the RF & microwave research field. The dielectric measurements are useful because they provide important information about the electric and magnetic properties of the materials under test (MUTs). The VNAs are widely used for material measurements and provide the material characterization in terms of scattering parameter (S-parameters) [1–4]. The S-parameters are further post-processed to obtain the permittivity of the MUTs [4]. However, the complete uncertainty estimation for permittivity measurements using the VNAs is still an open and active research topic. Even the recent works on material measurements using the VNA system are limited to the uncertainty due to VNA residual deviations of the pre-calibration only [3]. Therefore, the complete uncertainty budget showing different uncertainty contributions is still missing. In this work we present a complete uncertainty evaluation along with uncertainty budgets for permittivity measurements of a non-magnetic material following a differential numerical approach [5–7]. The uncertainty analysis is carried out for complex-valued S-parameters. The S-parameter uncertainty is linearly propagated to the complex-valued permittivity, where \( \varepsilon_r = \varepsilon'_r - j\varepsilon''_r \), and the MUT (Figure 2) is shown in The dimensional measurements of both the sample and the fixture are also performed. The propagation of uncertainties due to S-parameters and the dimensional measurements are carried out to compute the total uncertainty of the permittivity results. The uncertainty propagation is compliant with the “Guide to the expression of the
uncertainty in measurements—(GUM)” [8]. The measurements are traceable to the SI (International System of units) through dimensional measurements. The traceability of the measurements is important for the comparison of the results obtained using different measurement systems. As an example, a sample of Teflon was used as MUT and a WR-90 VNA waveguide setup was used as measurement system. The complete uncertainty budgets at different frequencies are also presented for permittivity results.

2. MEASUREMENT MODEL AND UNCERTAINTY ANALYSIS

The VNA measurement model used is described in Ref. [5] [see Eq. (1)] in which uncertainties are associated to the error terms. It includes the VNA noise, linearity, drift, cable stability and connector repeatability contributions related to S-parameters. This model has been implemented in a data acquisition software package. The measured transmission S-parameter ($S_{21}$) of the MUT in the X-band is further post-processed to compute the complex-valued permittivity in an iterative way by solving the following equation [4]:

$$S_{21} = e^{-j\gamma_0 L} \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2},$$

(2)

where, $\Gamma = \frac{\gamma_0 - \gamma_1}{\gamma_0 + \gamma_1}$, $T = e^{-j\gamma_1 L}$, $\gamma_0$ and $\gamma_1$ are the propagation constants in air and the material sample of length $L$, respectively. $L_w$ is the length of the waveguide fixture. $\gamma_0$ and $\gamma_1$ depend on the width of the waveguide fixture. The air gap corrections are also applied for the air gap that exists between the sample and the waveguide fixture. The air gap corrections are the function of the height of the waveguide fixture and the sample [4]. The dimensional measurements of the fixture and the sample have been performed and shown in Table 1. Their tolerance is 10 $\mu$m.

The VNA setup has been previously characterized in terms of noise, linearity, drift, cable stability and connector repeatability and the different S-parameter uncertainty influences have been computed [9]. The permittivity results also include the uncertainty contribution due to dimensional tolerances of the fixture and the sample dimensions.

The uncertainty propagation from the S-parameters to the permittivity results has been carried out by using a general purpose library, known as Metas.UncLib [6] and a custom MATLAB [10] code. This library allows the propagation of variances of the input probability density functions (pdfs) through a measurement model, taking the correlations between the quantities fully into account. Metas.UncLib uses differentiation techniques and keeps track of the dependencies throughout the measurement model [6,7].

3. EXPERIMENTAL RESULTS

Measurements have been performed with a two-port VNA in a temperature and humidity controlled shielded room. The temperature and the relative humidity during the measurements were of $(23.0 \pm 0.3)^\circ\text{C}$ and $(45 \pm 5)^\%$ respectively. The VNA was calibrated using the Thru-Reflect-Line (TRL) calibration technique [11]. This technique requires a direct (thru) connection between the two test ports, one port reflect standard of unknown reflection at both test ports and a line standard to calibrate the VNA. The Teflon sample has been machined to fit inside the WR-90 waveguide fixture which was also used as line standard during the TRL calibration. The measurement frequency ranges from 8.2 to 12.4 GHz. The permittivity results included the dielectric constant ($\varepsilon_r$) and the dielectric loss tangent ($\tan\delta$).

| Table 1 Dimensional Measurements of Waveguide Fixture and the Teflon Sample (in mm) |
|----------------------------------|-----------------|-----------------|
| Waveguide fixture | 9.78 | 22.86 | 10.17 |
| Teflon sample | 9.76 | 22.76 | 10.13 |

Figure 1 Schematic of the measurement setup

Figure 2 Layout of the waveguide fixture and the MUT

Figure 3 Dielectric constant ($\varepsilon_r$) for the Teflon sample
The measurement results and the uncertainty budgets for the dielectric constant and the dielectric loss tangent for the Teflon are presented here. The expanded uncertainties have been computed with a coverage factor of \( k = 2 \). The behavior of \( \varepsilon_r \) and \( \tan \delta \) as function of frequency including the uncertainty are shown in Figures 3 and 4.

Teflon has low dielectric constant (\( \varepsilon_r = 2.03 \) [12]) and very low dielectric loss tangent in the X-band (\( \tan \delta < 4 \times 10^{-4} \) [12,13]). From Figure 3, it can be seen that the measured dielectric constant results closely correspond to the known dielectric constant values for Teflon in X-band waveguide. The dielectric loss tangent shown in Figure 4 is also lower than the typical loss tangent values for Teflon in X-band waveguide. The behavior of \( \varepsilon_r \) and \( \tan \delta \) as function of frequency including the uncertainty are shown in Figures 3 and 4.

The uncertainty budgets for the Teflon sample showing different uncertainty contributions for \( \varepsilon_r \) and \( \tan \delta \) are shown at selected frequencies in Tables 2 and 3. The uncertainty contributions include both S-parameter uncertainties and the dimensional uncertainties. The uncertainty contributions are cable stability (Cable Stab.), connector repeatability (Conn. Rep.), drift, linearity (Lin.), noise and dimensional uncertainty (Dim. UNC). The different uncertainty contributions have been square root summed to form the combined standard uncertainty (Std. UNC.). It can be observed from Table 2 that the cable stability uncertainty has the most significant influence on \( \varepsilon_r \), while the connector repeatability, the VNA linearity and the dimensional uncertainty have significant influence on \( \tan \delta \). However, compared to dimensional uncertainty, the S-parameter uncertainty has dominant contributions to the permittivity results.

### TABLE 2 Uncertainty Budget for the Teflon Sample at Selected Frequencies for the Real Part of Permittivity (\( \varepsilon_r \))

| Freq./GHz | \( \varepsilon_r \) | Cable | Conn. | VNA | VNA | VNA | Dim. | Unc. | Std. Unc. |
|-----------|----------------|-------|-------|-----|-----|-----|------|------|-----------|
| 8.2       | 2.0269         | 0.0052 | 0.0010 | 0.0001 | 0.0006 | 0.0002 | 0.0037 | 0.0065 |
| 9.2       | 2.0224         | 0.0047 | 0.0006 | 0.0001 | 0.0005 | 0.0001 | 0.0039 | 0.0062 |
| 10.2      | 2.0243         | 0.0043 | 0.0002 | 0.0001 | 0.0004 | 0.0001 | 0.0039 | 0.0058 |
| 11.2      | 2.0269         | 0.0042 | 0.0001 | 0.0001 | 0.0003 | 0.0002 | 0.0039 | 0.0057 |
| 12.4      | 2.0282         | 0.0043 | 0.0002 | 0.0001 | 0.0003 | 0.0002 | 0.0039 | 0.0058 |

### TABLE 3 Uncertainty Budget for the Teflon Sample at Selected Frequencies for the Dielectric Loss Tangent (\( \tan \delta \))

| Freq./GHz | \( \tan \delta/10^{-6} \) | Cable | Conn. | VNA | VNA | VNA | Dim. | Unc. | Std. Unc. |
|-----------|----------------|-------|-------|-----|-----|-----|------|------|-----------|
| 8.2       | 4.0            | 1.8   | 1.9   | 0.1 | 1.2 | 0.3 | 2.1  | 3.6  |
| 9.2       | 1.9            | 0.1   | 0.7   | 0.1 | 0.7 | 0.1 | 0.7  | 1.3  |
| 10.2      | 3.3            | 0.4   | 0.4   | < 0.1 | 0.7 | 0.2 | 0.5  | 1.1  |
| 11.2      | 4.7            | 0.3   | 0.2   | < 0.1 | 0.7 | 0.2 | 0.2  | 0.9  |
| 12.4      | 20.7           | 0.9   | 1.1   | 0.1 | 1.4 | 0.4 | 0.5  | 2.1  |

4. CONCLUSION

In this article, a fully comprehensive measurement uncertainty analysis for permittivity results has been presented. This analysis allows the optimization of the setup with regards to the measurement uncertainty by analyzing the influence of different uncertainty sources. Results are also metrologically traceable to the SI through dimensional measurements. A Teflon sample has been measured from 8.2 to 12.4 GHz using a WR-90 VNA waveguide setup. The expanded uncertainties have been used, iteratively, to compute the complex-valued permittivity. The linear propagation of uncertainties through the measurement model has been carried out. The permittivity results agree very well to the known properties of the Teflon sample in the X-band. The uncertainty budgets are also presented at different frequencies. The results highlight that the cable stability has the major influence on the dielectric constant of the Teflon sample. Therefore, one should minimize the cable movements during the VNA measurements to get accurate measurements. Dimensional measurements are also critical. For what concerns the loss tangent, the most influential contributions are related to dimensional measurements, connectors repeatability and cable stability.

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A 60-GHz MULTI-BEAM ANTENNA ARRAY DESIGN BY USING MHMICs TECHNOLOGY

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ABSTRACT: The integration feasibility of two technologies including Miniaturized Hybrid Microwave Integrated Circuit (MHMIC) and Printed Circuit Board (PCB) are experimentally demonstrated at millimeter wave frequencies through the design of a switched beam antenna array. A 1 × 4 array of aperture coupled patch antennas etched on a RO5880 substrate is fed by a 4 × 4 butler matrix etched on a piece of high permittivity ceramic substrate. By using the proposed combined fabrication technologies, the feeding part on the ceramic substrate can be easily integrated with MHMIC active component, while the radiation part is individually improved. Comparison of simulated and measured results show that the proposed switched beam antenna offers a −10 dB matching bandwidth of 6 GHz ranging from 58 GHz to 64 GHz and a multi beam radiation pattern which is focused in 45°, 15°, −15°, −45° directions. © 2016 Wiley Periodicals, Inc. Microwave Opt Technol Lett 58:1844–1847, 2016; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29926

Key words: millimeter-wave; MHMIC technology; Butler matrix

1. INTRODUCTION

Recently, the use of unlicensed 60 GHz band has drawn significant attention due to increasing demand of ultra-high data rate communications over 1 Gbit/s for the wireless local area network (WLAN) and short range multimedia download [1]. As a paramount component of such communication links, different kinds of millimeter wave antennas have been proposed so far [2–6]. In most of these works, high gain antennas have been developed to overcome the propagation path loss of this frequency band and hence improve the system signal-to-noise ratio. Besides, employing an antenna array with a beam forming property is also required to achieve directive radiation beams in the desired spatial directions [7,8]. Beam forming can be cost-effectively realized by using a Butler matrix network, which provides appropriate phases and amplitudes as excitations of array elements according to the desired beams’ directions [9–11].

In this perspective, selecting an appropriate material platform for system integration is an important task in the design of a low cost, compact, and high performance beam forming structure. Having excellent high-frequency performances, there are many new thin materials such as liquid crystal polymer (LCP), low temperature co-fired ceramic (LTCC), and ceramic which have been explored for millimeter wave applications [7,10,11]. Among them, ceramic technology has received considerable attentions for antenna/microwave applications specifically because of its inherited low-loss and high dielectric constant features. Indeed, this results in realization of an efficient and compact circuit design at such high frequency range. In addition, the ceramic substrate is compatible with the usual 100 μm thick MMIC active component for integration, in which MMIC chips are placed in rectangular cuts on the ceramic allowing easy wire bonding with MHMIC components [12]. Although, ceramic is optimal choice for millimeter-wave frequency band, integrating an array antenna with a feeding network on the same substrate causes to deteriorate the antenna radiation pattern and its efficiency [12]. Separating antenna and feeding network is deemed to be an effective approach to enhance the antenna radiation pattern and its bandwidth.

In this work, to address this challenging problem, ceramic multilayer lamination capability has been investigated by integrating a piece of ceramic material (MHMIC technology) with RO55880 substrate (PCB technology). Therefore, a 60 GHz circuit characterization of passive MHMIC element on thin ceramic substrate has been carried out to build a Butler matrix that is used as a feeding network of an aperture coupled patch antenna array. Although, demonstrated with linearly polarized aperture coupled patch element, this structure can be used with different planar radiating elements to have other radiation characteristics such as circular polarization or higher gain performances, while the passive beam forming network can be easily integrated with other active circuits such as LNA and switches.

2. DESIGN OF BUTLER MATRIX AND ANTENNA

The proposed 60 GHz switched beam antenna consists of a 4 × 4 Butler matrix and a 1 × 4 aperture coupled patch antenna array as illustrated in Figure 1. In this structure, in order to avoid the adverse influence of the feeding network on the antenna radiation pattern and also have a high efficient radiator, the Butler matrix and antenna array have been implemented with two different substrates. The antenna array is etched on a piece of RT/duroid 5880 substrate with \( e_r = 2.2 \) and thickness of 254 μm, while the feeding network is etched on a piece of thin ceramic material with \( e_r = 9.9 \) and thickness of 127 μm. Two substrates are stacked together with a thin layer of glue with \( e_r = 3.4 \) and thickness of 5 μm. Indeed, by utilizing this structure...