A Useful New Class of Miniature CPW Shunt Stubs and its Impact on Millimeter-Wave Integrated Circuits

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Abstract—This paper proposes a new concept for the generation of millimeter-wave coplanar waveguide (CPW) shunt stubs printed within the center conductor, as opposed to those printed in the ground plane. Several new designs are presented for CPW open- and short-end shunt stubs patterned inside the center conductor. Unlike conventional stubs, which are patterned inside the ground plane, several advantages are derived from the use of the proposed framework: additional degrees of freedom, lower radiation loss, high compactness, and a reduction of the number of air bridges that are potentially expensive to build. The way to achieve high-quality circuits is detailed and confirmed by experimental results over the large frequency band from 1 to 50 GHz. Good agreement between experimental and theoretical results, obtained using two different full-wave techniques, validates the design procedure. In an effort to explore the advantages offered by the proposed CPW shunt stubs, in terms of their flexibility and potential for innovation, a possibility of the usage of such stubs in the area of filters is investigated. Thus, three novel variants of miniature filters are designed and measured, demonstrating that the proposed shunt stubs are entirely responsible for major reduction of size and better performance. The designs presented here show a new powerful way of achieving size, weight, and cost reduction. They are suitable to be used as building blocks for the growing commercial radio-frequency/millimeter-waves wireless communications circuits and systems.

I. INTRODUCTION

RESONATORS form the basic design elements in many microwave components. Advances in microwave and millimeter-wave integrated circuits mandate that high-performance planar resonators be used as building blocks for low-cost and highly sophisticated communication systems. Today, while the subject of resonators is mature, there is relatively little literature on coplanar waveguide (CPW) resonators [1]–[3].

Using uniplanar technology, sophisticated circuit elements can be designed, which are mostly not realizable using conventional microstrip technology [4], [5]. In the early days of CPW technology, some basic CPW elements were proposed by Houdart [6] and Holder [7] which are basically short- and open-ended 90° transmission-line resonators connected in series or parallel. In uniplanar technology, series resonator elements can be either implemented in the “inner” or “outer” conductor of the CPW [8], [9]. On the other hand, until now, the CPW shunt stubs are mainly printed in the “outer” conductor of the CPW [10], [11].

To show the wide range of flexibility and scope of innovation that CPW uniplanar technology offers, and to improve the performance of the existing CPW elements, the first part of this paper demonstrates several new designs of millimeter-wave CPW shunt stubs patterned inside the center conductor. The capability to generate shunt stubs within the center conductor relaxes the limitations inherent in the realization of low- and high-impedance levels. Different variations of these stubs are fabricated, and accurate on-wafer measurements are performed over a large frequency band (1–50 GHz). The realization of these shunt stubs is detailed and confirmed with theoretical and experimental results.

While the field of filters is now very mature, there is relatively little literature on CPW filters [12]–[19]. To fill this void, Section II of this paper presents a viable way to implement three different filters (low-pass and bandpass) involving the proposed shunt stubs. A fifth-order semilumped uniplanar low-pass Chebyshev filter is designed, fabricated, and measured. It is found that such a filter has the following advantages compared to the ladder-type filter: very wide stopband with a lower number of elements (no spurious responses up to 20 GHz), higher cutoff rate, lower insertion and radiation losses, and higher compactness (a significant 30% reduction of the circuit area when compared to the ladder type).

Moreover, a compact bandpass filter configuration, with multiple poles of attenuation at the quarter-wave frequency and dc blocking, is designed and measured. This filter takes advantage of the harmonious coexistence between the proposed CPW shunt stubs and the standard CPW series stub. This possibility greatly expands the freedom in design and gives a new powerful technique, which opens the ways to a
large number of new possibilities for hybrid and monolithic millimetric integrated circuits with good integration density.

II. NEW CLASS OF MINIATURE CPW SHUNT STUBS PATTERNED IN THE CENTER CONDUCTOR

Fig. 1 shows a new class of CPW shunt stubs printed in the center conductor along with their analogous stubs printed in the ground plane. Basically, a portion of the ground plane in the form of a thin strip is introduced across the CPW, and the inner conductor is jumped across this using air-bridges. Stubs to ground are then formed within the center conductor using the new local ground point. For comparison purposes, Fig. 2 shows the difference between the series CPW stubs and shunt stubs printed in the center conductor.
In comparison with the conventional CPW shunt stubs, the following advantages are obtained from the use of the proposed new shunt stubs.

1) One of the most promising aspects of the new CPW shunt stubs is their compactness, which provides both low-loss and longitudinal symmetry. It is also noted that the location of the stubs within the center conductor leads to greater field confinement and, thus, lower radiation loss.

2) The lateral extent of the circuits is minimized by utilizing the center conductor for the stub pattern, allowing the use of smaller shielding cavities without affecting the stub performance.

3) Reduction of the number of air bridges in case of asymmetric CPW shunt stub (shown at the top of Fig. 1), which are potentially expensive to build, is another advantage.

4) One attractive feature is that all of the new CPW shunt stubs exhibit transverse symmetry around the center conductor. Thus, theoretically, the parasitic coupled slotline mode should not be excited in these structures. On the other hand, in the case of the conventional asymmetric shunt stub, two transverse air bridges have to be used, besides the longitudinal air-bridge, so that the coupled slotline mode is not excited in the feeding lines.

In order to show the potential of the new proposed class of CPW shunt stubs, several CPW shunt stubs have been fabricated. Fig. 3 shows the schematic of the tested CPW shunt stubs patterned in the center conductor. These circuits are designed near $f_0 = 30$ GHz and implemented on high dielectric constant substrate $\varepsilon_r = 9.9$ and $h = 0.254$ mm. This is close to the dielectric constant of GaAs, which demonstrates the feasibility of integrating this new class of CPW shunt stub into monolithic circuits. Fig. 4 shows the measured $S$-parameters of the tested CPW shunt stubs along with theoretical results obtained using two different techniques: the integral equation technique solved with the moment method and complex images [20], and the finite-difference time-domain (FDTD) method [21].
Fig. 4. Experimental and theoretical results for the different new CPW shunt stubs.

III. CONFIGURATION FOR LOW IMPEDANCE LEVELS USING THE MULTISTUBS CONCEPT

The conventional CPW shunt stubs covers an impedance range from approximately 30–80 Ω. Values outside this range cannot be fabricated reliably and could cause excessive losses. For several applications, however, it is desirable to use either very large or very small characteristic impedance levels. For example, the difficulty in realizing low- or high-impedance levels using conventional shunt stub constitutes a serious limitation in filter design, particularly at high frequencies. While the upper limit of realizable characteristic impedance is set by manufacturing tolerances, the lower limit depends on the onset of higher order modes, which occur when the transverse dimension becomes comparable to the wavelength or longitudinal dimension. This, in effect, leads to substantial discrepancies between predicted and actual performances when lower and higher values are realized. To overcome this difficulty, it is advantageous to adopt the concept of parallel connection of many single CPW resonators, as illustrated in Fig. 5. In this way, the total line impedance can drastically decrease and the above disadvantages can be removed.

IV. IMPACT OF THE NEW CPW SHUNT STUBS ON FILTER IMPLEMENTATIONS

A. New Variant of Miniature Low-Pass Filters

Due to the versatility of the uniplanar technology, the proposed CPW shunt-stub topologies are adopted to extend the
stopband bandwidth of low-pass filters and remove a number of limitations inherent to the conventional design approach [see Fig. 6(a)]. Two alternative topologies are shown in Fig. 6 along with the classical configuration. The utilization of series CPW stubs patterned in the center conductor combined with high-impedance line sections, and the use of the proposed CPW shunt stubs combined with low-impedance line sections, allow to realize configurations of uniplanar low-pass filter in compact form. As illustrated in Fig. 6(b) and (c), capacitors are realized by the joint utilization of low-impedance line sections with a very small electrical length and CPW shunt stub in balanced form, while the inductors are realized from series stubs integrated in the low-impedance line sections combined with high-impedance line section with a very small length.

B. Alternative Design of Compact Bandpass Filters

In order to compare the performance of the classical and new low-pass filter topologies, three experimental circuits were designed and fabricated on EPSILAM substrate ($\epsilon_r = 10$, $h = 0.255$ mm). The fifth-order Chebyshev filter investigated consists of three inductive line ($Z_c = 166$ $\Omega$) and two capacitive lines ($Z_c = 23$ $\Omega$). Its cutoff frequency is 3 GHz with 0.1-dB ripple. The elements of the filter are calculated using a standard design procedure [22]. The experimental results of the classical and compact low-pass filters are shown in Fig. 7. It can be observed that both compact filters do not present any significant degradation in terms of bandwidth. In comparison with the classical structure, the advantages that may be derived are: 1) very sharp rejection slope; 2) high compactness; 3) lower insertion loss in passband; 4) lower radiation loss; and 5) very wide stopband with a low number of elements [the spurious responses are rejected at higher frequencies up to 20 GHz for the configuration shown in Fig. 6(c)].

A typical topology of a CPW bandpass filter is shown in Fig. 8(a), which consists of a cascade of alternate quarter-wavelength CPW shunt stubs and quarter-wavelength CPW connecting lines. Due to the versatility of the proposed CPW shunt stubs, a possible way of fabricating a millimeter-wave bandpass filter with shunt stubs in an inner conductor form is shown in Fig. 8(b), in which the Kuroda identity is used. A three-section short-end shunt-stub bandpass filter was fabricated using the proposed CPW shunt stubs patterned in the center conductor. The filter is centered at 30 GHz with 50% bandwidth. It has a Chebyshev response with 0.01-dB
ripple where the synthesis procedure of this filter type is described in [22]. The total dimensions of the new compact filter are \(1\lambda_0\) long at 30 GHz (4.45 mm) and 0.65-mm wide. This circuit have been fabricated on Alumina substrate \((h = 0.254\) mm, \(\varepsilon_r = 9.9\)). The measured response is presented in Fig. 9, which indicates that, in the whole bandwidth, the reflection coefficient is lower than \(-23\) dB with a flat insertion response with a maximum attenuation of 2 dB (including radiation, dielectric, and conductor losses). It is worth noting that the theoretical results in Fig. 9 are generated by using the scattering parameters found from the full-wave analysis of a shielded lossless single stub and treating the filter as three uncoupled elements in parallel. This explains the zero insertion loss in the passband seen in the moment-method results. The agreement between the measured and calculated performance is quite good and indicates that there is very little electromagnetic coupling between the stubs, even though the stub separation is only 100 \(\mu\)m.

C. Ultraminiature Multistub Bandpass Filter

Previously, different CPW bandpass filters have been published, but most of them are based upon the use of lumped or distributed CPW elements [23]–[26]. The bandpass filter consists of a ladder of lumped series and parallel LC resonators. For most of the integrated technologies, such as microstrip, a direct synthesis with distributed elements is difficult due to...
Fig. 9. Experimental and theoretical results of the new compact bandpass filter.

Fig. 10. Novel implementation of multistub configurations at one junction. (a) Short-end shunt and open-end series CPW stubs implemented in the outer and inner conductor of the CPW, respectively. (b) Short-end CPW stub inside open-end CPW stub printed within the center conductor.

To realize the required cluster of stubs at a single junction, which can be accomplished by means of the Kuroda identities. However, in uniplanar technology, the required cluster of stubs could be realized at a single junction. An original illustration of the cohabitation of different CPW stubs is shown in Fig. 10(a). This junction structure can be easily constructed as a combination of shunt and series CPW stubs. However, miniaturizing such a device with broad-band characteristics is a key technology. Therefore, a CPW shunt stub printed inside a series CPW stub (both printed within the center conductor) offer attractive features [see Fig. 10(b)]. This possibility greatly expands the freedom in design and gives a powerful technique for designing original structures with good integration densities.

Therby, novel configurations of multistubs bandpass filters have been realized to demonstrate the efficiency of the design method and the pertinence of the joint utilization of the multistubs configuration at one junction to get better performance. However, a precise study is necessary to understand the elec-
The electromagnetic behavior of such configurations to be able to use them in bandpass filter design. Therefore, the development of more accurate uniplanar models, based on full-wave analysis, is key to improvement of microwave and millimeter-wave circuit simulations and reducing lengthy design cycle costs. It has been shown that the relative flexibility of the complex image and FDTD methods makes them attractive tools for the analysis and design of these complex circuits [20], [21]. This step is illustrated via the circuit presented in Fig. 11. This circuit is implemented on high dielectric constant substrate $\varepsilon_r = 9.9$ and $h = 0.254$ mm. Good agreement between the full-wave analysis and measurement is observed. The differences could be attributed to the fact that dielectric and conductor losses are neglected in both the FDTD and moment-method analyses.

2) Filter Experiments: Two multistub bandpass filter configurations seem appropriate, as illustrated in Fig. 12(a) and (b). The ultraminiature configuration, i.e., Fig. 12(b), which appears to have some merit, would involve the new CPW shunt stub printed within the standard CPW series stubs. The structure have been designed at center frequency of 20 GHz with bandwidth of 100% following guidelines given in [22]. The experimental results of this filter are plotted in Fig. 13 along with simulated results. This bandpass filter configuration, with multiple poles of attenuation at the quarter-wave frequencies and dc blocking, allows a high degree of compactness with good skirt selectivity for very wide bandwidth. In general, in the whole bandwidth, the measured return loss is lower than $-18$ dB with the insertion loss not exceeding 1.5 dB (including radiation, dielectric, and conductor losses). These losses can be reduced by widening the dimensions of the central conductor of the coplanar line so as to minimize metallic loss. Besides, the filter provides a very high rejection outside the passband.

V. CONCLUSIONS

Microwave and millimeter-wave integrated circuits using uniplanar technology yield innovative and high-performance components and subsystems. This study has focused on several new designs of CPW shunt stubs patterned in the center conductor. The experimental results indicate that these new CPW shunt stubs have a major part to play in the miniaturization of monolithic microwave integrated circuits (MMIC’s) in the future. Compared to the existing CPW shunt stubs printed in the ground plane, the advantages that may be derived from the new stubs are: 1) additional degrees of freedom; 2) lower radiation loss; 3) high compactness; 4) smaller shielding cavities to be used without affecting the performance; and 5) reduction of the number of air bridges that are potentially expensive to build.

It has been shown that the relative flexibility of the FDTD method, and the accuracy and computational efficiency of the integral equation technique, along with the complex image Green’s functions, make them attractive tools for the analy-
sis and design of these complex circuits. Experimental and theoretical results have been presented to verify the validity of the design, and very good agreement between theory and experiment was obtained.

Due to the versatility of the uniplanar technology, the proposed CPW shunt-stub topologies were adopted to build new filter topologies that remove a number of limitations inherent to the conventional design approach. Uniplanar technology, contrary to the microstrip technology, allows the realization of very compact bandpass filters with good performance. These performances are achieved with the utilization of multistubs at one junction. Both shunt and series stubs patterned at one junction have found a fruitful application in the multistub bandpass filter synthesis by providing additional degrees of freedom and resulting in extremely compact configuration that are attractive for passive and active monolithic integrated circuits.

Finally, the results of this study on the new shunt stubs indicate several potential applications as building blocks for the emerging wireless communications industry, in general, and in the design of low-cost uniplanar microwave and millimeter-wave circuits such as filters, mixers, and antennas in particular.

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REFERENCES


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