Miniaturized Synthetic Rectangular Waveguide

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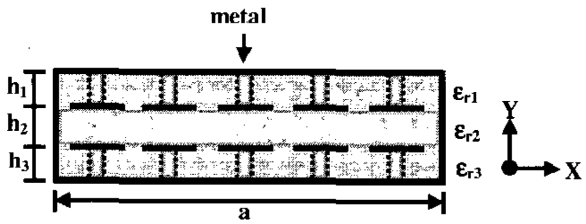
***Abstract* — An artificially engineered, dielectric-filled rectangular waveguide is presented. Such synthetic waveguide, made by conventional printed-circuit board (PCB) process, consists of two-dimensional periodical arrays at the top and bottom surfaces and two metallic sidewalls. A synthetic waveguide of cross-section 8.0 mm by 0.609 mm, relative permintivity (ε_r) 3.38, shows cutoff frequency at 4 GHz with normalized propagation constant asymptotically approaching 4.5 at frequencies much greater than the cutoff frequency. Rigorous measurements show that the extracted dispersion curves agree well with theoretical data, demonstrating the feasibility of size reduction of the synthetic rectangular waveguide breaking the well-known limit of $1/\sqrt{\varepsilon_r}$ imposed on the conventional rectangular waveguide. Measured data show that the slow-wave factor is 185% higher and cutoff frequency 61.9% lower when comparing the synthetic waveguide with the conventional waveguide of identical dimensions and material constant.**

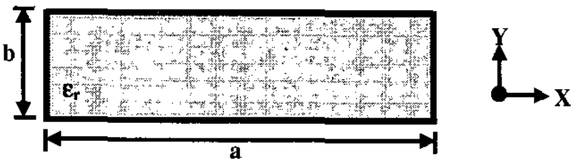
I. Introduction

Multi-layered low-temperature-cofired-ceramics (LTCC) and printed-circuit board (PCB) technology have been widely applied in modern microwave-integrated-circuits (MIC) designs for wireless application. Planar and quasi-planar guiding structures such as microstrip, stripline, and coplanar waveguide are the common choices for MIC circuit designs in the multi-layered LTCC and PCB. These guiding structures are subject to a variety of loss mechanisms, e.g., conductor losses, dielectric losses, radiation losses, leakage effects [1-2], rendering degraded circuit performance. To overcome these losses, researchers commenced rethinking of the ways we made MICs in the past. Recently Zaki et al reported a high performance LTCC evanescent mode ridge waveguide filter at X-band [3-4], Tzuang et al a H-planar PCB filter at Ka-band [5], Wu et al a shorting-pin PCB filter at Ka-band [6]. All of them employed novel planar to waveguide mode converters, and designed the high-quality filters in the form of rectangular waveguide. They embedded these high-performance filters made of rectangular waveguides into the complete LTCC or PCB planar module.

The fundamental physics and design techniques of the rectangular waveguide have been well established and widely applied by microwave engineers. The MIC rectangular waveguide, which is filled by higher dielectric constant material, can operate at lower frequency with smaller size using the dominant waveguide mode, say TE_{10} mode. Subsequently, the physical size of waveguide can also be reduced using the evanescent mode design techniques [3]. The cutoff frequency of the MIC rectangular waveguide is inversely proportional to the square root of ε_r. ε_r is the relative dielectric constant of the filling material. Various kinds of MIC circuits incorporating rectangular waveguide had been developed to show the versatility [7]. This paper reports a new technique to break the physical limit of $\sqrt{\varepsilon_r}$ imposed on the conventional rectangular waveguide for size reduction. The new approach for designing planar rectangular waveguide makes use of two-dimensional periodical array patterned at the top and bottom surfaces of the waveguide. This new waveguide can propagate energy at much lower frequency with much slower phase velocity when comparing with the conventional all-metallic rectangular waveguide. The theory and design principles of the proposed waveguide are described in section II. Both theoretical and experimental results are presented in Section III to depict the guiding characteristics of the proposed MIC rectangular waveguide and illustrate the synthetic nature of such waveguide in a sense that the cutoff frequency of the waveguide is no longer dictated by the $1/\sqrt{\varepsilon_r}$ rule. Section IV concludes the paper.



(a) Synthetic rectangular waveguide



(b) Conventional all-metallic rectangular waveguide

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Fig.1. **Miniaturized synthetic rectangular waveguide** a=7mm, b=0.609mm,h_1=h_2=h_3=0.203mm, ε_{r1}=ε_{r2}=ε_{r3}=3.38, tanδ1=tanδ2=tanδ3=0.002, metal thickness=17 μm, via diameter=0.25mm.

II. SYNTHETIC RECTANGULAR WAVEGUIDE: DESIGN AND OPERATIONAL PRINCIPLE

The concept of synthetic rectangular waveguide is illustrated in part (a) of Fig. 1. The two-dimensional periodical array substitutes both top and bottom metallic surfaces of the conventional rectangular waveguide as shown in part (b) of Fig. 1. Various kinds of the periodical arrays have been reported [8-9]. These periodic arrays made of printed technology, conduct DC currents but not AC currents within the stopband. Such two-dimensional periodical arrays show electrical properties of high impedance surface and therefore known as the magnetic conductor surface (within the stopband). Moreover, Itoh et al reported that UC-PBG (Uniplanar Compact Photonic Bandgap) ground plane significantly changes the guiding characteristics of the microstrip, increasing the slow-wave factor for the operating frequencies below the first stopband [10]. Tzuang et al reported that EME (Electric-Magnetic-Electric) microstrip changes the dispersion characteristics of the microstrip at higher order, reducing the required line width of the conventional uniform microstrip for keeping the same onset frequency of the EH1 leaky mode [11]. This paper extends the slow-wave concept for size reduction to the design of miniaturized rectangular waveguide. As shown in Fig. 1, the two-dimensional periodical array resides on both longitudinal (z-axis) and transverse (x-axis). Assuming that the vertical dimension in the y-axis of the waveguide is much smaller than the lateral dimension so that only TE_{m0} modes can propagate. When the TE_{m0} modes propagate in the waveguide, which contains the vertical transverse E fields and H fields perpendicular to E fields, both H fields and E fields are perturbed by the periodical arrays at top and bottom surfaces of the guide. Such perturbations result in the slow-wave effects, and consequently the proposed rectangular waveguide has much higher normalized phase constant and lower cutoff frequency than those of the conventional rectangular waveguide surrounded by all-metallic walls.

The proposed waveguide is made by multi-layered print-circuit-board technology. Referring to Fig.1, the two-dimensional periodical array is made on a two-sided printed RO4003^{TM} circuit board of thickness (h_1,h_3) 0.203mm and relative permittivity (ε_{r1},ε_{r3}) 3.38 to form the top and bottom surfaces of the waveguide. Similar two-dimensional periodical structures had been reported for design an EME (Electric-Magnetic-Electric) microstrip acting as a slow-wave line [9]. Another RO4003^{TM} dielectric substrate intended for a prepreg layer in a typical PCB process (ε_{r2}=3.38, h_2=0.203mm) is sandwiched between the top and bottom surfaces formed by the two periodical arrays. As shown in Fig.1, the vertical sides of the rectangular waveguide are made by plated-through technology followed by thick copper plating of 17 μm to complete the rectangular waveguide design.

III. DISPERSION CHARACTERISTICS OF THE SYNTHETIC RECTANGULAR WAVEGUIDE

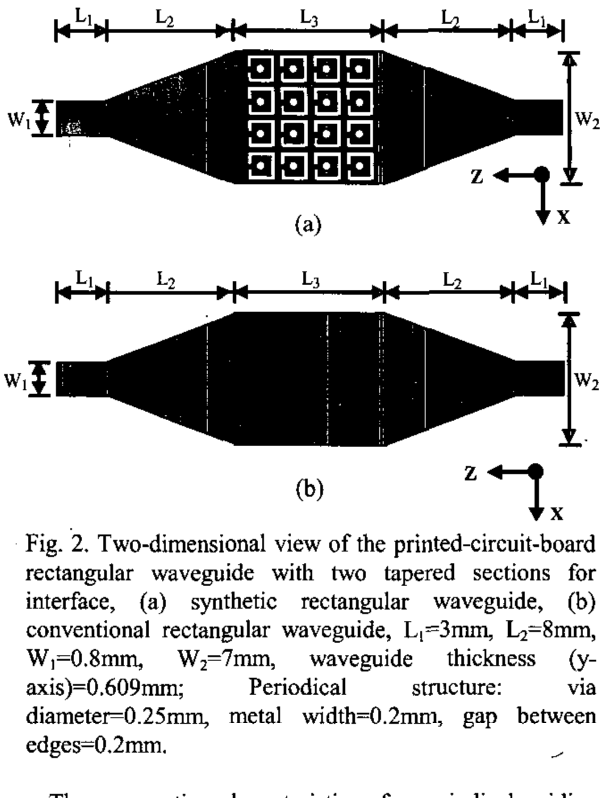
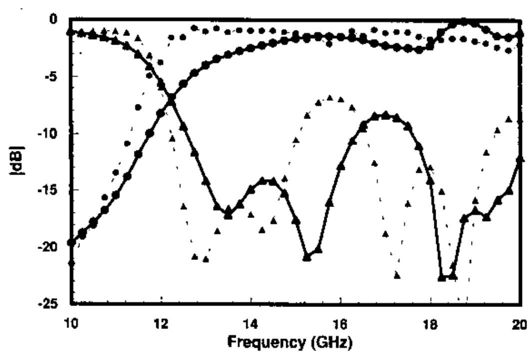
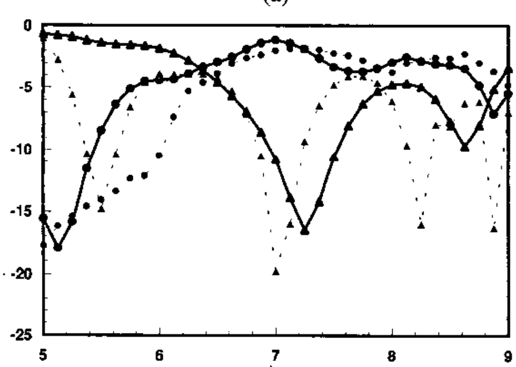


Fig. 2. Two-dimensional view of the printed-circuit-board rectangular waveguide with two tapered sections for interface, (a) synthetic rectangular waveguide, (b) conventional rectangular waveguide, L_1=3mm, L_2=8mm, W_1=0.8mm, W_2=7mm, waveguide thickness (y-axis)=0.609mm; Periodical structure: via diameter=0.25mm, metal width=0.2mm, gap between edges=0.2mm.

The propagation characteristics of a periodical guiding structure can in principle be obtained by invoking the Floquet theorem [12], but the proposed rectangular waveguide under studies consists of microstrip-to-waveguide transition, in addition to the main rectangular waveguide section. Part (a) of Fig. 2 shows the top view of the proposed synthetic rectangular waveguide. The microstrip taper acts as the mode converter to provide a smooth interface between the rectangular waveguide and other planar circuits [7]. To compare the dispersion characteristics of the synthetic waveguide and the conventional waveguide, two identical waveguides together with identical interface except the main body sections as shown in Fig. 2 are built and tested. Fig. 3 plots the theoretical and experimental two-port scattering parameters of the guiding structures shown in Fig. 2(a) and (b), respectively, showing good agreements between the theoretical and measured data. Notice that the microstrip-to-waveguide transitions of the two rectangular waveguides are identical and two waveguides are filled with the same dielectric material of permittivity 3.38. The passband frequency of the proposed synthetic rectangular waveguide is approximately 50% lower, implying that the synthetic rectangular waveguide should propagate at much lower frequency although its dimensions are identical to those of conventional rectangular waveguide.



(a)

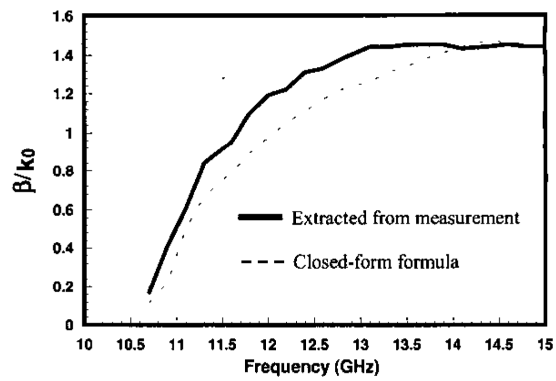


(b)

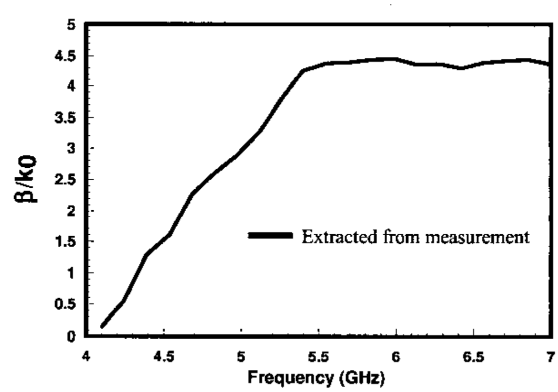
Fig.3. Scattering parameters of Fig. 2 (a) conventional rectangular waveguide filled with dielectric material (ε_r=3.38), (b) synthetic rectangular waveguide

-●- simulated S_{21},- ● -measured S_{21}, —▲— simulated S_{11}, -▲- - measured S_{11}.

Fig. 4 shows the normalized phase constants extracted from the measured results of the rectangular waveguides by de-embedding the effects of the microstrip-to-waveguide transitions. The well-know TE_{10} mode formula from textbook is invoked for comparison, showing that the extracted dispersion curve agrees reasonable well with the formula as shown in Fig. 4(a). On the other hand, Fig. 4(b) shows that the cutoff frequency of the proposed synthetic waveguide is 61.9% lower and 185% higher than those of the conventional rectangular waveguide.



(a)



(b)

Fig.4 Measured dispersion characteristics of the de-embedded rectangular waveguide, (a) conventional rectangular waveguide, (b) synthetic rectangular waveguide.

IV. Conclusion

A new approach for designing miniaturized rectangular waveguide is presented. The conventional rectangular waveguide is reconfigured by substituting the top and bottom plates by the two-dimensional periodical arrays, thus forming a synthetic rectangular waveguide. The theoretical and experimental data show the cutoff frequency of the proposed synthetic rectangular waveguide 61.9% lower, and the slow-wave factor 185% higher when compared with conventional rectangular waveguide of the same cross-sectional dimensions.

Acknowledgement

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