Broadband TEM-Mode Planar-Rectangular Dielectric Waveguide Bandpass Filter and Its Miniaturization

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Abstract - **This paper presents a novel design method of a two-pole, low-profile, high performance broadband planar-rectangular dielectric waveguide bandpass filter (BPF) using a λ/2 TEM-mode resonator, where there is no hole, no dent or any other discontinuity in the BPF structure. Keeping the electrical performance almost unchanged, the miniaturization technology of the BPF is proposed. All of the BPF models are verified by electromagnetic simulation.**

I. Introduction

Direct metal-coated dielectric resonator BPFs are well known for their versatile use in electronic and communication systems due to their high performance, low cost, lightweight, and compact size in comparison with other types of commercially available filters. Most commonly used direct metal-coated BPFs are TEM-coaxial resonator BPFs, where there is a hole inside each of the resonator [1] - [2]. Several planar TE/TEM-mode metal-coated BPFs are proposed in [3]-[4], where coupling between resonators is provided by making hole, dent, slit or other irregular shape.

However current super compact mobile communication devices demand ultra thin (thickness ≤ 1mm), high performance and low cost BPFs. In case of co-axial resonator BPFs, if we make the BPF thickness about 1mm, the unloaded quality factor will reduce drastically and simultaneously the BPF structure will fail to provide sufficient mechanical strength for commercial use. In the case of planar waveguide BPFs, where the coupling between resonators is provided by creating some irregularities, it will also fail to provide necessary mechanical strength.

The objective of the current invention is to develop an ultra thin, high performance, low-cost and low profile planar-rectangular dielectric waveguide BPF, where there is no hole, no dent, no slit and no irregular shape in the BPF structure. The filter should be a piece of planar-rectangular dielectric material, directly covered with metal patterns.

II. Resonator Structure and Coupling

Fig.1 shows the physical structure of a λ/2 TEM-mode planar-rectangular dielectric waveguide resonator. The

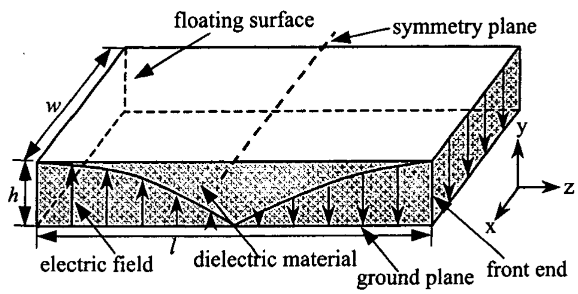

Fig. 1. Electric field distribution of a λ/2 TEM-mode planar -rectangular dielectric waveguide resonator.

temperature coefficient, $\tau_f = \pm 5$ ppm/^{0}c. The top and bottom surfaces of the resonator are directly coated with silver. The rest of the surfaces are open to the air. The bottom surface is grounded and top surface is floating. The electric field distribution is shown along the direction of propagation (z-axis). The electric field varies sinusoidally along the direction of propagation. It becomes maximum (positive or negative) at the two open ends and minimum (zero) in-between these two ends. We have named the zero electric field line as the symmetry plane.

The resonant frequency (f) of the dominant mode of a λ/2 TEM-mode planar waveguide resonator can be calculated by using the following relation

$$f = \frac{c}{2 \times l \sqrt{\varepsilon_{eff}}} \tag{1}$$

where c is the velocity of light in free space, l is the length of the resonator along the direction of propagation and ε_{eff} is the effective dielectric constant, which can be defined as

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10h}{w}\right)^{-.5} \tag{2}$$

where ε_r is the relative permittivity of the dielectric material, h is the thickness and w is the width of the resonator.

From the above equations we observe that the resonant frequency of the resonator mainly depends upon its length.

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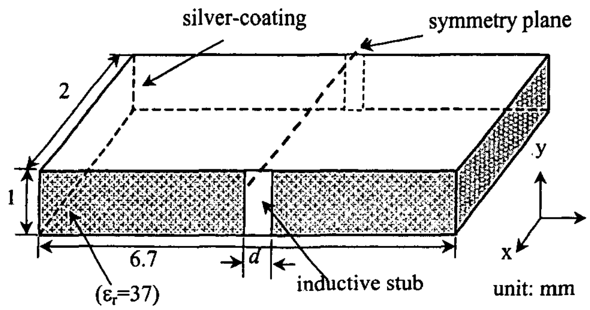


Fig. 2. TEM -mode λ/2 resonator with added inductive stub.

GHz resonant frequency, the optimized resonator dimensions become: 6.7mm × 2mm × 1mm (Fig.2). If two inductive stubs of similar dimensions are placed in symmetry with the symmetry plane and parallel with the electric field, the $TE_{11\delta}$-mode propagating along the z-direction will be excited in addition to the dominant TEM-mode [5]. If we increase the length (d) of the stub the TE-mode resonant frequency will be increased with little increase of the TEM-mode resonant frequency. When the symmetry plane is short-circuited it will represent TEM-mode and for open circuit condition it will represent TE-mode and coupling is possible between these two hybrid-modes. Now we have simulated the TE and TEM mode frequency for 0.2 mm increment of the inductive stub length from 0.2 mm to 2.2. The simulated values are shown in Fig. 3. We observe that with the increase of *d*, the hybrid mode frequencies become closer to the TEM-mode frequency. The calculated coupling constant between the two hybrid modes is shown in Fig. 4. We find out that with increase of *d*, the coupling constant decreases curvilinearly.

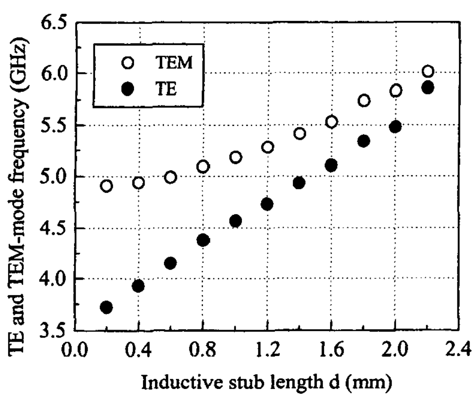


Fig. 3. TE and TEM-mode frequency vs. inductive stub length.

Since the electric field is maximum at the two open front ends of the resonator, capacitive excitation should be more efficient there. The external circuit coupling i.e., the external quality factor can be controlled by changing the dimensions of the excitation electrode.

A maximally flat two-pole BPF is designed for center frequency of 5.25 GHz and 10.5% i.e., 550 MHz 3-dB bandwidth [6]. The necessary coupling coefficient between two modes becomes 0.074, which can be obtained for inductive stub length of 1.8 mm (Fig. 4). Hence, the necessary external quality factor becomes 13.9. To obtain this, the front-end capacitive excitation electrode

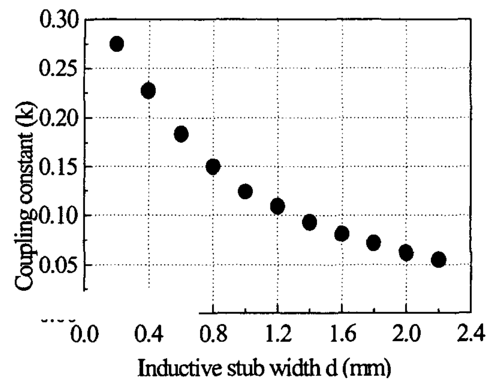


Fig. 4. Coupling constant vs. length of stub.

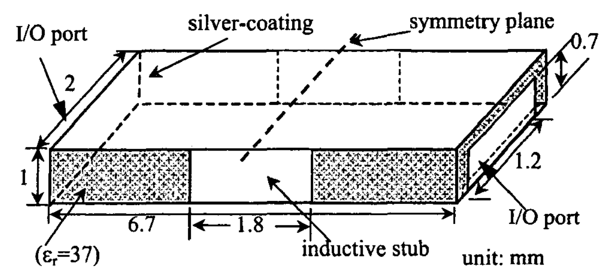


Fig. 5. Invented BPF structure for hybrid-mode coupling.

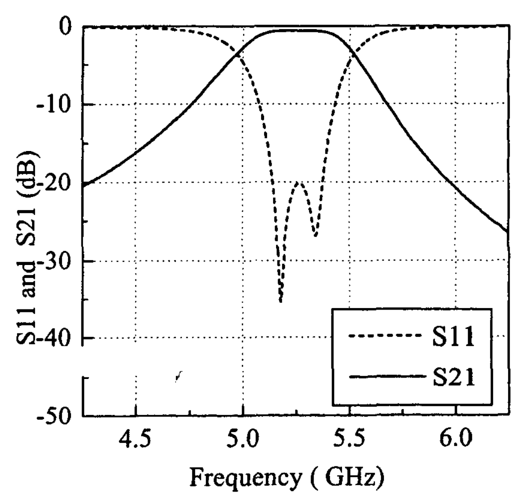


Fig. 6. Simulated electrical performance of the BPF.

dimensions become: 1.2 mm × 0.7 mm. Finally, the invented planar-rectangular BPF structure becomes as of Fig. 5. This BPF structure is simulated considering all the losses (radiation, conductor and dielectric) by using the commercially available high frequency structure simulator

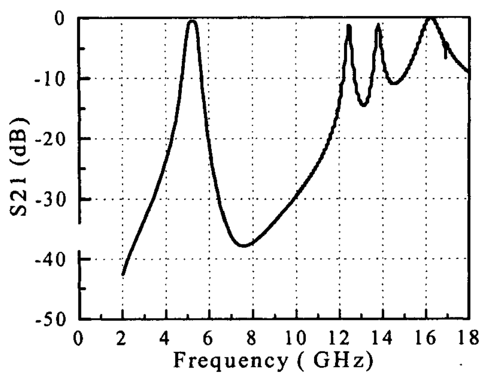
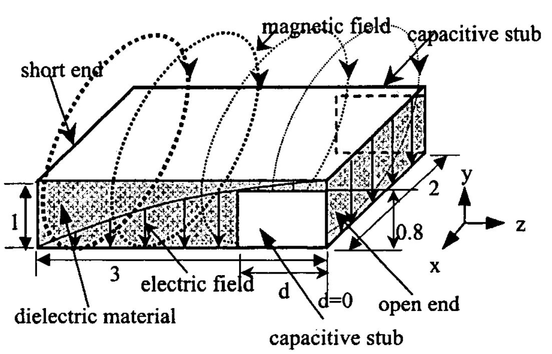


Fig. 7. Spurious performance of the simulated BPF.

(HFSS). The effective conductivity of the silver coated resonator was taken as 60% to that of the bulk silver [6]. The simulated transmission and reflection coefficient of the BPF is shown in Fig. 6. This filter has an excellent in-band and out-of-band electrical performance, with insertion loss of 0.6 dB, 3-dB bandwidth of 545 MHz, and center frequency of 5.25 GHz. The spurious transmission performance of the BPF is shown in Fig. 7.

III. MINIATURIZATION OF THE BPF

The electromagnetic field distribution of a λ/4 TEM-mode planar dielectric waveguide resonator is shown in Fig. 8. We observe that the electric field varies sinusoidally along the direction of propagation (z-axis). The electric field is maximum at the open end and minimum (zero) at the short end. Contrary to the electric field, the magnetic field is minimum at the open end and maximum at the short end (the thickness of the dotted line indicates the intensity



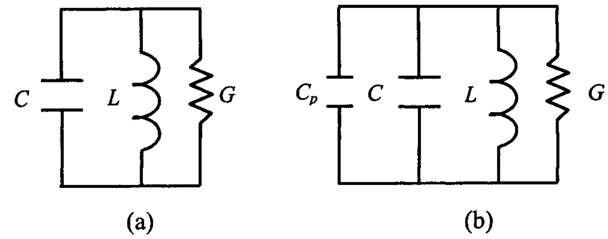


Fig. 9. Equivalent circuit of the λ/4 resonator.

of the magnetic field). The equivalent circuit of the resonator is described in Fig. 9 (a) (excluding capacitive stubs). The resonant frequency of this circuit can be calculated using the following equation

$$f_1 = \frac{1}{2\pi\sqrt{LC}} \qquad (3)$$

Now if we add electrodes perpendicular to the electric field and in the electric field dominating area (as shown in Fig. 8), the electrodes will act as capacitive stubs and add a parallel capacitance (C_p) to the resonator equivalent circuit as shown in Fig. 9 (b)[7]. The value of C_p will increase with the increase of the capacitive stub dimensions in the electric field dominating area.

Hence the resonant frequency of the added capacitance (C_p) circuit can be calculated as follows

$$f_2 = \frac{1}{2\pi\sqrt{L(C+C_p)}} \qquad (4)$$

From equation (4) we notice that, with the increase of C_p the resonant frequency decreases, although the length of the resonator remain unchanged.

The unloaded quality factor (Q_0) of the parallel *L-C* circuit can be calculated using the following relation

$$Q_0 = \frac{2\pi f_2 (C+C_p)}{G} \qquad (5)$$

Since f_2 decreases with the increase of C_p, from equation (5) we can assume that the Q_0 value would be compensated up to a certain length of the capacitive stub. At the same time, the electric field changes sinusoidally along the direction of propagation. Hence, the effect of the capacitive stub should reduce with the increase of the stub length *d*, i.e., the stub will no longer act as a capacitive stub when the length of *d* enters the magnetic field dominating area. To prove the above concept, we have taken a λ/4 TEM-mode resonator as of Fig. 8(including capacitive stub), having dimensions of 3 mm × 2mm × 1 mm. Then we placed capacitive stubs at both sidewalls of the resonator. Keeping the stub height constant at 0.8 mm, we have increased the length *d* and have measured Q_0 and f_2 of the resonator. The measured values are shown in Fig.10. We have observed that with the increase of *d*, the resonant frequency decreases up to $d \cong 1.6$ mm and then increases.

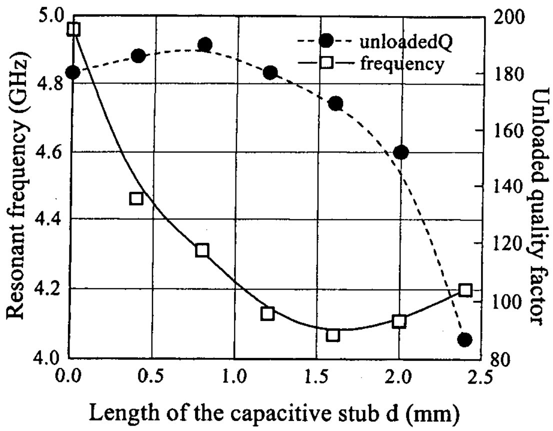


Fig. 10. Measured Q_0 and f_2 vs. length of the capacitive stub.

Considering the Q_0 value and f_2 value, we can conclude that the optimum value of the stub length *d* should be about half of the resonator length.

Using the above mentioned miniaturization technology we have designed a BPF to obtain similar electrical performance to that of the BPF shown in Fig. 6. This new BPF structure is shown in Fig. 11. Four capacitive stubs of similar dimensions are placed symmetrically at the two sidewalls. The simulated performance of the BPF is shown in Fig. 12, having a resonant frequency of 5.25 GHz, insertion loss of 0.75 dB, and a 3-dB bandwidth of 510 MHz. In comparison with Fig. 6, since the 3-dB bandwidth is decreased from 545 MHz to 510 MHz, the insertion loss is increased by 0.15 dB. If we compare with Fig. 5 and Fig. 11, we observe that for this particular case the length of the BPF is reduced by 1.4 mm (about 21%). But the electrical performance remains almost unchanged.

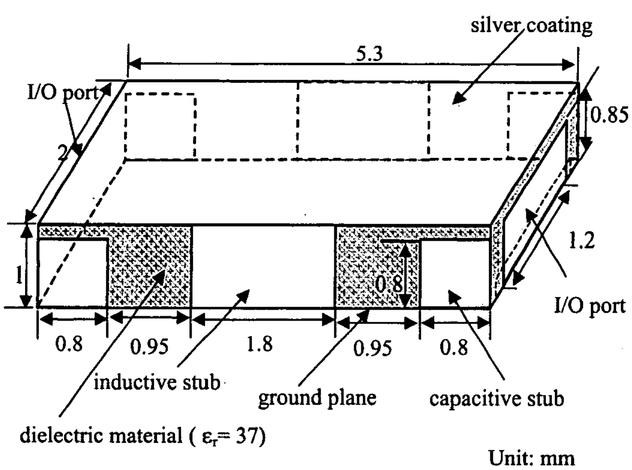


Fig.11 Configuration of the BPF with added capacitive stub.

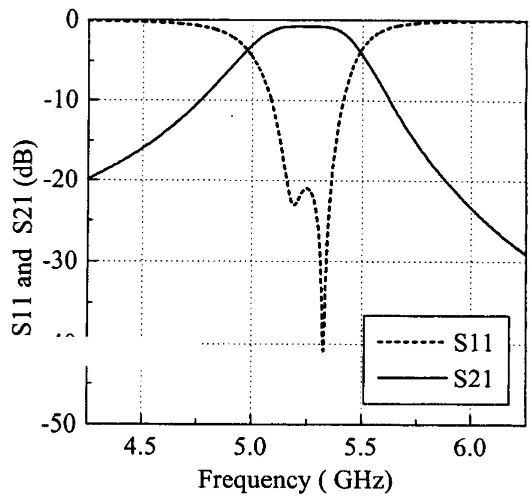


Fig. 12. Simulated electrical performance of the BPF for added capacitive stub.

V. Conclusion

To cope with the future demands for wireless communication terminals and other communication devices, we have designed an ultra thin, high performance, low-cost planar-rectangular dielectric waveguide BPF, where there is no hole, no dent or any other discontinuities in the BPF structure. We also have proposed its miniaturization technology and have verified it by HFSS.

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