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A 3D-Printed Lightweight X-band Waveguide Filter Based On Spherical Resonators

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***Abstract*— A 5th order X-band waveguide bandpass filter, based on spherical resonators, has been designed, and fabricated by 3D printing. In comparison with rectangular waveguide, spherical resonators have a higher unloaded quality factor, but at the same time suffer from closer higher order modes. In this paper, a special topology has been proposed to relieve the impact of the first three higher order modes in the resonator and ultimately to achieve a good out-of-band rejection. Stereolithography based 3D printing is used to build the filter structure from polymer and a 25 μm thick copper layer is deposited to the filter. The measurement result of the filter has an excellent agreement with the simulations. The filter is also considerably lighter than a similar metal filter.**

***Index Terms*—3D printing, filter, stereolithography, spherical resonators, waveguide.**

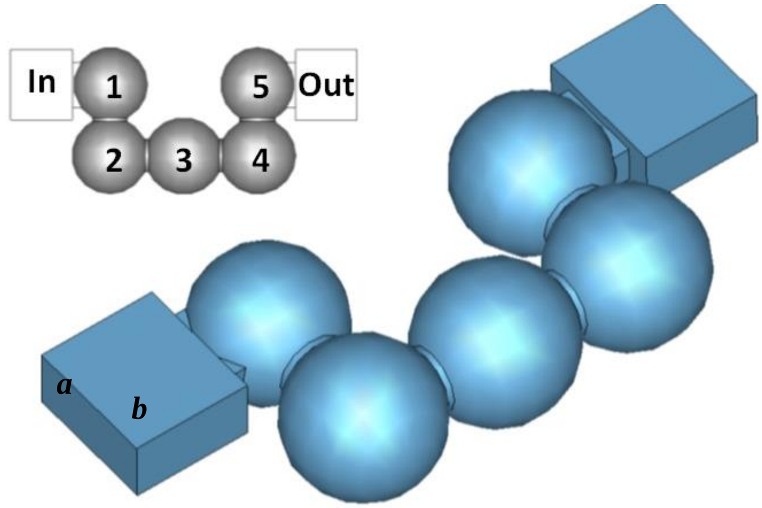

Fig.1. Configuration of X-band filter based on 5 spherical resonators. The insert shows top view of the filter. a=22.86 mm, b=10.16 mm.

I. Introduction

WAVEGUIDE components have been used in communication systems for many years. This is mainly due to their great advantage of low loss as well as higher power handling capacity compared to microstrip and coaxial devices. In the recent years, 3D printing (or additive manufacturing) has attracted an increasing interest due to its great potential in a wide range of areas. There are many types of 3D printers working with polymers, which can be utilized to construct the structure of microwave components, these components can then be metal coated to form a conductive surface. These PoP (Plating on Plastic) components are much lighter compared with conventional metal ones. The biggest advantage of applying 3D printing, to the fabrication of microwave components, is that the part under construction is built layer by layer so the cost depends on the volume instead of complexity. This enables designers to incorporate complex shapes in their designs, such as small slots in a horn antenna as reported in [1]. Three types of 3D printing processes, namely, FDM (Fused Deposition Modeling), SLA (Stereo-Lithography) and SLS (Selective Laser Sintering), have been utilized to fabricate waveguide filters [2], dielectric filters [3]-[4] and horn antennas [1], [5]. SLA and SLS are similar processes since they both use a beam of laser to solidify material powder or liquid photopolymer resin layer by layer. FDM works by depositing melted ABS plastic from a nozzle and it usually has a relatively poor resolution. SLA was chosen in this work as it has been reported to have a high resolution and a good surface quality [6].

The filter is designed based on spherical resonators which have very high unloaded quality factors. A diagram of the filter is shown in Fig. 1. The fabrication of such spherical shape resonators is a challenge, to the conventional CNC (Computer Numerical Control) milling process. This problem was addressed by 3D printing due to its flexibility to structure shapes. The use of spherical resonators in the filter design was reported some time ago, e.g. [7], here five degenerate modes were used in a single resonator to make a five pole filter. However, as discussed in [8], degenerate modes would degrade the Q (because of the use of many tuning screws) as well as the power handling capacity. Additionally, the use of higher modes will create unwanted passband as discussed in [9]-[10].In this paper we have utilized spherical resonators operating at fundamental TM_{101} mode to achieve a high unloaded Q and proposed a new topology to reject the first three higher modes.

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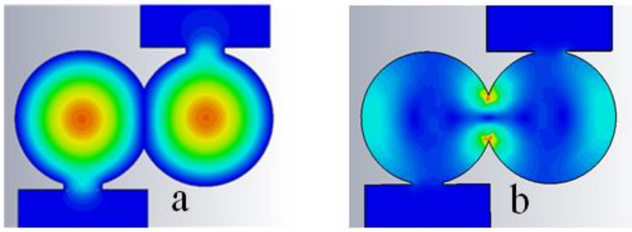

Fig. 2.Magnetic field distributions of (a) $H_{\varphi,TM101}$ and (b) $H_{\varphi,TM211}$.

II. Filter Design

The filter was designed by following the coupled resonator filter theory as described in [11]. It is designed to have a Chebyshev response, with a center frequency of 10 GHz, a bandwidth of 0.5 GHz (FBW=5%) and a passband return loss of 20 dB. The non-zero coupling coefficients and the external quality factors are calculated to be: $Q_{e1}=Q_{e5}$=19.4279, $M_{12}=M_{45}$=0.0433, $M_{23}=M_{34}$=0.0318. The final structure of the filter is shown in Fig. 1 and its corresponding simulation results can be found Fig. 3. Magnetic fields of both the dominant mode as well as the first three degenerate modes can be expressed as [12]

$$
\begin{aligned}
H_{\varphi,TM101} &= A/\sqrt{r}\cdot J_{3/2}(kr)\sin\theta \\
H_{\varphi,TM201} &= A/\sqrt{r}\cdot J_{5/2}(kr)\sin(2\theta) \\
H_{\varphi,TM211} &= A/\sqrt{r}\cdot J_{5/2}(kr)\cos(2\theta)\cdot\cos\varphi \\
H_{\varphi,TM221} &= A/\sqrt{r}\cdot J_{5/2}(kr)\sin(2\theta)\cdot\cos(2\varphi)
\end{aligned}
\tag{1}
$$

When the angle of the coupling iris on the θ axis is 90º, $H_{\varphi,TM101}$ reaches its maximum value while $H_{\varphi,TM201}$ and $H_{\varphi,TM221}$ become zero (i.e. the impact of these two modes are suppressed). Similarly, when the coupling iris is placed at 90º on φ axis, the dominant mode remains unchanged but the cosφ term in $H_{\varphi,TM211}$ becomes zero. Fig. 2 shows the magnetic field distributions of the dominant mode as well as $H_{\varphi,TM211}$ when the coupling mechanism discussed above is used. Based on this principal, a topology for which there is a 90° turn at every resonator, should offer the best out-of-band rejection performance, as shown in Fig. 3. Here we call this type of topology as "Olympic topology" for it looks like the Olympic rings. Ultimately, "Ω topology" (as shown in Fig. 1) is employed in this work as it offers similar performance but is much easier to fabricate. The simulation results for the Ω topology, Olympic topology, Line topology (without any rejection mechanism) together with a conventional H-plane filter based on rectangular resonators are given in Fig. 3. The comparison of S_{21} responses indicates that Ω topology improves the rejection level by around 22 dB (at 12.4 GHz) in comparison with Line topology. The Olympic topology provides an extra 6 dB rejection than Ω topology but it is 9 dB lower than the rectangular filter.

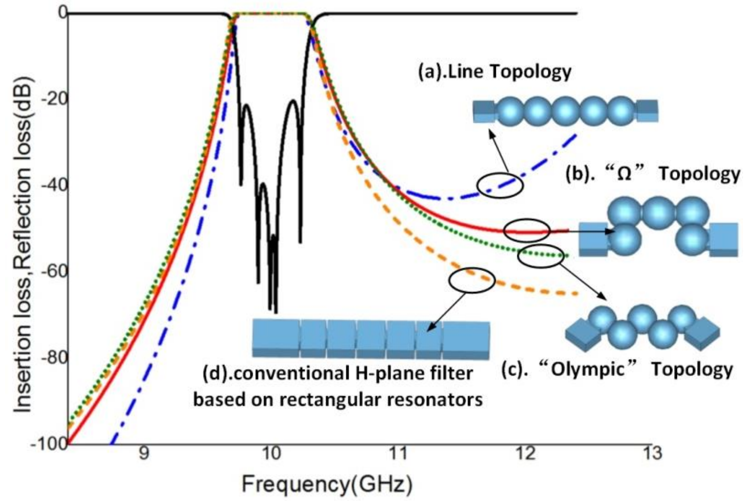

Fig.3. Simulation results of the filters with different topologies: (a) Line topology without any higher modes rejection mechanisms; (b) "Ω topology" with considerable rejection and it is utilized in this work; (c) "Olympic topology" with the best rejection; (d) A H-plane filter based on rectangular resonators

TABLE I
COMPARISON OF THREE TYPES OF RESONATORS

	Unloaded Q	Dimensions (mm)	Second-mode frequency (GHz)
Rectangular	7957	22.86×10.16×19.9	15.1 (TE_{201})
Cylindrical	11200	10 (radius)×31.5(height)	13 (TE_{112})
Spherical	14450	13.1 (radius)	14.1(TM_{2m1})

The main reason we use spherical resonators is the quality factor of a spherical resonator is high. The unload Q of a spherical resonator working on TM_{101} mode at 10 GHz is around 14450 whilst the value for a rectangular one is 7957 (both calculated using the conductivity of copper. i.e. 5.97×10^7 S/m). The Q of a cylindrical resonator working at the same frequency is also calculated. The radius of the resonator is chosen to be 10 mm and unloaded Q for the TE_{111} mode is 11200. In order to compare the pros and cons of these resonators, a comparison of several key factors of these resonators is given in Table 1. In the table frequencies where the second mode appears are also given. As the table shows, the Q of the spherical resonator is 1.816 times than the rectangular one. On the other hand, the volume is doubled. The increase in volume is a disadvantage at X-band but could be an advantage for the same design operating at higher frequencies (e.g. W-band) where a larger volume facilitates the fabrication process and reliefs the requirement on dimensional accuracy. In order to achieve an even higher unloaded Q for a single resonator, higher modes inside a spherical resonator can be utilized (as reported in [13]) here it mentions that the TE modes have a higher Q than TM modes. For example, for TE_{101} mode, the diameter of the resonator will increase by 1.637 times, and the theoretical unloaded Q will increase from 14450 to 30850 at 10 GHz, as we calculated. For filter design, it would be difficult to use it because there are many modes nearby and it's difficult to reject them. However, in some narrow-band applications such as oscillators, those higher modes can be employed to achieve an ultrahigh Q.

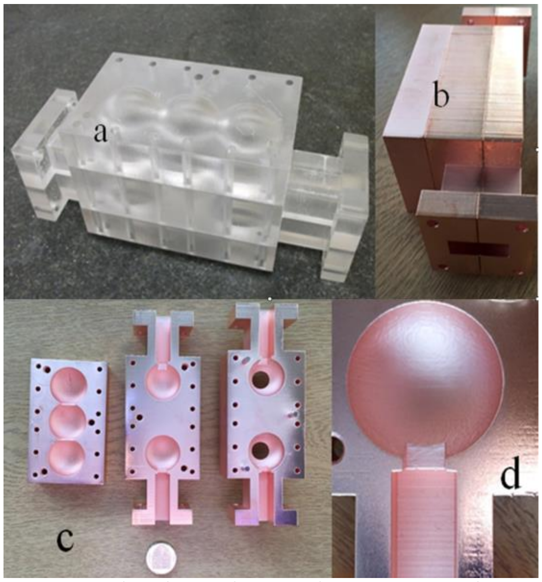

Fig. 4. Photographs of the filter before and after plating. (a) Before plating; (b) and (c) after plating; (d) enlarged view of one spherical resonator.

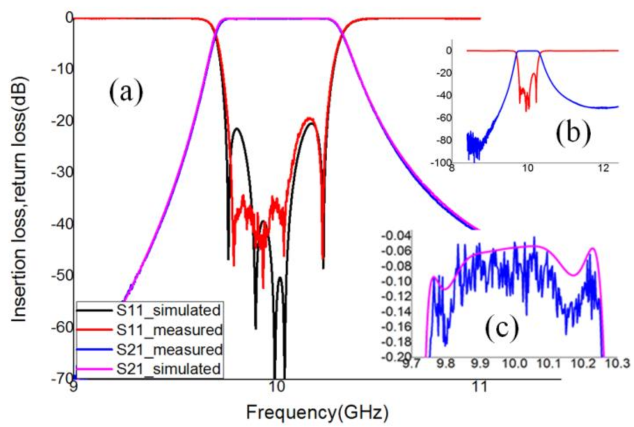

Fig. 5. Simulation and measurement results of the filter. (a) Responses over the frequency range of 9-11 GHz; (b) Measured responses over the whole X-band. (c) Enlarged view of the insertion loss performance over passband.

III. Measurements and Discussions

The structure of this filter was fabricated using SLA in 3D Systems, and then coated with a 25 μm layer of copper. It should be noted that this 25 μm thick copper has been taken in consideration during the filter design. The photos of this filter before and after plating are shown in Fig. 4.The filter was split into three pieces to facilitate the plating process which requires access to the inner surface. The simulated as well as measured results of this filter are depicted in Fig. 5. The measurement results (no tuning used) are in good agreement with simulations. Frequency shifts upwards by 5 MHz (0.05% of the center frequency). The measured passband insertion loss is 0.107 dB on average, while the simulated value is 0.072 dB, as shown in Fig. 5 (c). The extra 0.035 dB loss is very small and it may be attributed to the combination of three factors: (i) imperfect connections to the VNA, (ii) the gaps between three layers of the filter (iii) the degradation of the surface conductivity due to the imperfection of the surface quality such as roughness. It should be noted that the polymer utilized by the filter has a working temperature of no more than 39-46 °C. For applications involving high temperatures, ceramic filled material which has higher working temperatures (up to 120-250 °C) could be used to print the same filter. The weight of this filter is 0.28 kg which is only 14% of that made from copper. Additionally, the weight can be reduced even further by removing much of the plastic materials.

IV. Conclusions

We have presented an X-band waveguide filter based on spherical resonators. New topologies have been proposed to reject the first few higher modes inside the spherical resonator. The structure of this filter was fabricated by 3D printing, and the device was then copper coated. This PoP device is only 0.28 kg that is much lighter than a copper device (2 kg). The measured frequency response has a good agreement with the design. It indicates the process has a good dimensional accuracy as well as the proposed filter structure is capable of providing an ultra-low insertion loss.

Acknowledgment

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