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SLM Printed Waveguide Dual-mode Filters with Reduced Sensitivity to Fabrication Imperfections

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***Abstract*— This letter presents a 8th-order dual-mode waveguide filter, fabricated using selective laser melting (SLM) technique. The filter employs four dimpled ellipsoid dual-mode resonators, operating at the fundamental TM_{101} mode. During printing, the filter can be mechanically self-supported without any internal supports. Compared to the filters employing tuning posts, the proposed filter is less sensitive to fabrication errors in terms of their impacts on passband return loss (RL), frequency shift and bandwidth. The filter was demonstrated at WR-112 band (7-10 GHz), with a measured insertion loss of 0.25-0.4 dB and a RL >15 dB across the passband of 8-8.46 GHz.**

***Index Terms*—Dual mode filter, ellipsoid resonator filter, SLM printing, 3-D printing.**

I. INTRODUCTION

3-D printing has been widely applied in the fabrication of microwave devices in the past few years. Among different types of 3-D printing techniques, stereolithography (SLA) has the ability to produce components with a better dimensional accuracy and surface finish compared with SLS/SLM [1]-[2]. SLA systems with printing resolution ranging from 25-50 µm have been used to demonstrate filters and other types of waveguide devices (e.g magic-Ts) at around 100 GHz [3]-[5]. Currently, the typical metal powder size for SLM systems is as large as 50 µm, making this technique more suitable for relatively low frequency devices, e.g. filters operating below 30 GHz or so [1], [6]. There exist very high accuracy SLM systems with powder size down to 5-10 µm, and a filter working above 100 GHz has been successfully demonstrated [7]. However, such systems are expensive and not readily accessible.

Filters are inherently narrowband devices and therefore are more sensitive to fabrication imperfections, particularly for filters with more complex structures. For instance, 3-D printed 4th and 8th-order dual-mode waveguide filters were reported in [8]-[9]. Both filters were printed using SLA in one piece with subsequent copper plating. Their measured *S*-parameter responses were found to be very sensitive to the dimensional imperfections, even the filters' centre frequencies are as low as 10 GHz. As a result, post tuning was undertaken for the 4th-order filter in [8], to improve the return loss (RL) in the passband from 12 dB to 18.6 dB. Tuning becames even more difficult for the 8th-order filter in [9], owing to filter structure being more complex.

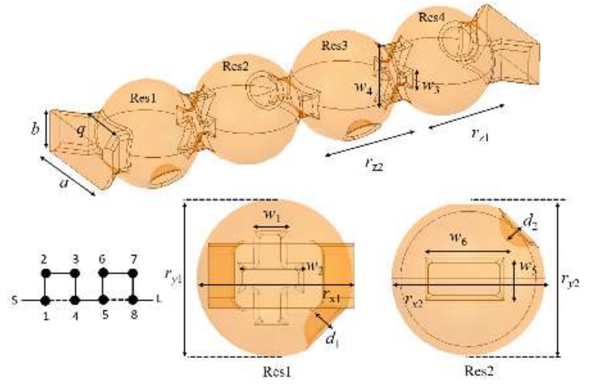

Fig. 1. The proposed 8th-order WR-112 filter based on dimpled ellipsoid dual-mode resonators. Critical dimensions in millimeters are: a=28.45, b=12.64, q=17.04, w_1=4.21, w_2=11.38, w_3=3.5, w_4=16.7, w_5=6.12, w_6=14.5, r_{z1}=28.99, r_{x1}=30.97, r_{y1}=30.84, d_1=4.31, r_{z2}=30.54, r_{x2}=31.30, r_{y2}=31.20, d_2=4.19.

Here, we have extended the works in [8]-[9] and reported on an improved dual-mode filter design with reduced sensitivity to dimensional errors. The proposed filter is comprised by dimpled ellipsoid resonators. The frequency tuning and mode coupling are realized by designing the shape of the resonators. The filter structure is mechanically self-supported, so that no additional supports are required during the printing. This facilitate the fabrication using the SLM technology and reduce post-fabrication treatment process. The design is demonstrated at WR-112 band using an 8th-order dual-mode filter, as shown in Fig. 1. Mode analysis of the resonator and sensitivity analysis for the filter show that the design is less prone to fabrication errors in terms of their impact on passband RL reduction, frequency shift and bandwidth deterioration . Hence, the proposed design could find useful application in massive production, where the yield can be largely improved and the demand for post tuning can be minimized or even eliminated.

II. DESIGN AND RESULTS OF THE 8TH ORDER FILTER

Dual-mode cavity filters are often designed using dual-mode resonators with some (usually three) tuning screws/posts on

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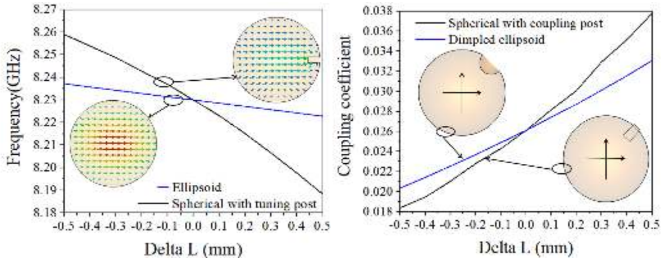


(a) (b)

Fig. 2. Resonant frequency and coupling variation versus dimension changes (Delta L) of two types of resonators.(a) Resonant frequencies. (b) Coupling coefficients between the two orthogonal modes in a dual mode cavity.

each cavity [8]-[14]. Intuitively, as the screws are generally much smaller than the waveguide cavity, they are likely to be more sensitive to the fabrication imperfections. Dual-mode filters without tuning screws (and posts) have also been studied. In [15]-[17], various of inserts with irregular shapes were placed into the cavity and/or rotation between cavities, location and rotation of the inserts were manipulated to replace the screws. However, these designs in [14]-[17] are tailored for CNC milling and are not ideally suitable for SLM printing. The printing quality of the filter can be poor for areas with overhang (supports need to be generated), large flat areas (with strong internal stress) and sharp corners [18]-[22]. Here, we have developed a dual-mode filter that overcomes the aforementioned shortcomings of the SLM printing.

A. Design of the 8th-order dual-mode filter

The filter is based on perturbated ellipsoid resonator with an organic shaped and self-supported structures, as shown in Fig. 1. As mentioned above, such physical structure is well suited for SLM printing as no shape corner, large flat areas and discontinuities exist inside the filter cavity. The characteristics of the filter structure also benefit reducing sensitivity of the filter performance against the fabrication imperfections. The coupling coefficient and resonate frequency of two types of dual mode resonators are studied and compared in Fig. 2. The fundamental mode for both the spherical and the ellipsoid resonator is TM_{101}. Hence, to alter the resonant frequency, a tuning post is usually placed along with the E-field of the resonator (similar to other type of dual mode resonators, e.g. cylindrical resonator [9]), whereas in the ellipsoid resonator, the orthomode frequencies can be altered by changing the small or large diameters. As shown in Fig. 2 (b), to realize the coupling between two orthogonal modes, another tuning post can be added to obtain the desired coupling coefficient. It is replaced by a perturbations (dimples) on the cavity itself in the new design. The relationships between the two critical quantities and the physical dimensions are compared in Fig. 2. It is clear that the sensitivity can be found from the slope of the curves. The slope of the ellipsoid is smaller than the spherical with posts, and therefore the ellipsoid approach is expected to be less sensitive to fabrication imperfections.

Based on the discussions above, the filter was designed based on the perturbated ellipsoid resonator, the specification was from a ground satellite link: centre frequency: 8.23 GHz, bandwidth= 0.46 GHz, passband insertion loss (IL) ≤ 0.5 dB and return loss ≥ 15 dB (VSWR<1.5). A pair of transmission zeros (TZs) were designed at $f_0 \pm 0.33$ GHz to satisfy a 40 dB rejection bandwidth of 0.65 GHz. The other pair of TZs were designed near 7.7 GHz and 8.9 GHz. Considering fabrication tolerance to the filtering performance, the the filter is designed with a targeted RL of 20 dB instead of 15 dB. The coupling coefficients and external quality factor of the filter were calculated to be [20]-[21]: $M_{12}=0.043$, $M_{23}=0.038$, $M_{34}=M_{45}=0.029$, $M_{14} = -0.0097$, $M_{58} = -0.0018$, $M_{56} = 0.029$, $M_{67} = 0.033$, $M_{78} = 0.045$, and $Q_{eS} = Q_{eL} = 18.74$. As shown in Fig. 1, the filter structure (except for the dimples) is mirror-symmetric from its center (between resonator 2 and resonator 3) while the dimples are located at positions of +/-90° to meet the phase requirements (i.e the negative couplings) in the coupling matrix [21]. The dimensions of the filter were extracted by following the approach in [18]. Fig.3 shows the simulation results of the filter. The conductivity of aluminum alloy (1.9×10^7 S/m) was used and the influence of surface roughness was not considered in the simulation.

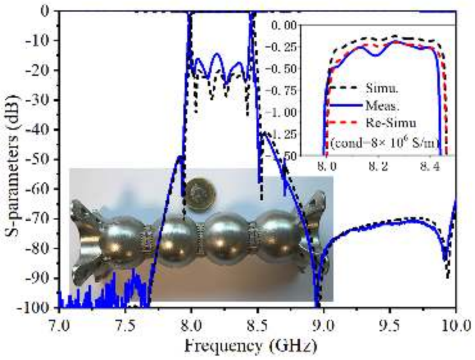


Fig. 3. Simulated and measured results (without tuning) of the 8th-order filter.

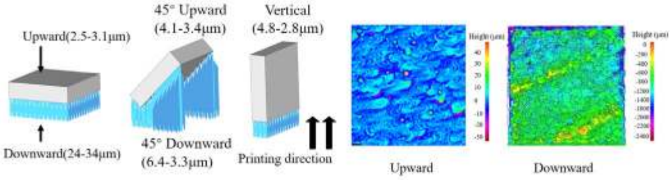


Fig. 4. Surface quality of the SLM printed samples with different printing directions.

B. Fabrication, measurements and surface roughness considerations

The filter was fabricated, from an aluminum-copper-based alloy (92 weight percent (wt. %) aluminum, 5 wt. % copper, and 3 wt. % others) supplied with a 15–53-µm particle size, using an SLM Solutions GmbH multi-laser SLM500HL system [23]. The system usually suffers from an uniform volume shrinkage of about 0.7-0.9% [24]-[25] so the filter model was enlarged for 0.8% in advance. Then, the filter was printed in a vertical posture and a vertical printing resolution of 50 µm was used. Together with the filter, some samples with 2×2×0.5cm^3 dimensions with different printing orientations were also

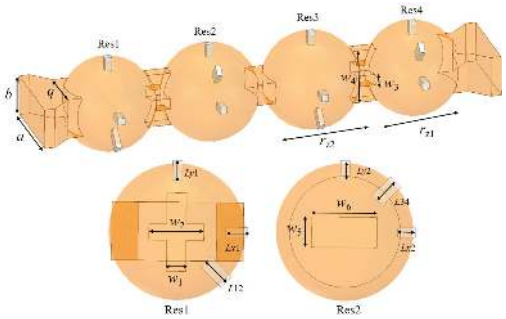
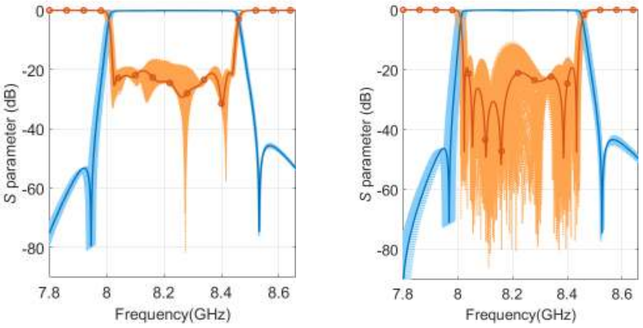


Fig. 5. The spherical resonator filter with conventional tuning posts (Filter B). Critical dimensions in millimeters are: a=28.45, b=12.64, q=13.36, w_1=4.24, w_2=10, w_3=12, w_4=1.8, w_5=12, w_6=1.8, r_{z1}=29.23, L_{x1}=3.7, L_{y1}=4.2, L_{12}=5.87, r_{z2}=30.38, L_{x2}=3.6, L_{y2}=3.6, L_{34}=5.21.



(a) (b)

Fig. 6. Sensitivity analysis of (a) ellipsoid dual-mode resonator filter in Fig. 1; and (b) spherical dual-mode resonator filter with tuning posts in Fig. 5.

TABLE I
PERFORMANCE COMPARISON OF TWO FILTERS

Performance	min(RL)	max(ΔBW)	max(Δf_0)
Dimpled ellipsoid filter	16.49 dB	17.7 MHz	8.5 MHz
Spherical filter with tuning posts	10.76 dB	30.5 MHz	15 MHz

TABLE II
COMPARISON WITH PREVIOUSLY REPORTED MULTI-MODE FILTERS

Ref	f_0 and FBW	Filter Order	RL (dB) Before tuning	RL (dB) After tuning	Δf (%)	IL (dB)	Resonator type	Fab
[8]	10/3	4	>12	>18.6	0.01	0.24	Spherical	SLA
[9]	8.23/5	8	>10	No tuning	0.16	0.32−0.68	Circular	SLA
[13]	12/(1-2)	2	>20	No tuning	<0.5	0.45-0.6	Spherical	SLA
[14]	6.54/1.8	3	N.A	20dB	<0.38	0.1	Spherical	CNC
[29]	11/7.3	8	>12	No tuning	<0.5	0.7	Rectangular	FDM
T.W.	8.23/5	8	>15	No tuning	<0.12	0.25-0.4	Dimpled Ellipsoid	SLM

printed and they were used for surface roughness measurements, as shown in Fig.4. The SEM images show that the surface roughness (Ra) is ranging from 2.5-6.4 µm for all faces except for the downward face (24-34 µm). Hence, as the filter was based on an organic shaped resonator and printed in a vertical orientation, no downward faces exist inside the structure so that the surface quality can be optimized. However, the surface roughness is still much higher than the SLA printed parts (e.g. 0.93-1.16 µm for all faces in [4]).

The fabricated filter and its measured response are shown in Fig. 2. Excellent agreements between the simulation and measurement was achieved: RL >15 dB, IL of 0.25-0.4 dB, frequency shift <10 MHz (<0.12%). The higher-than-designed IL is mostly attributed to the non-zero surface roughness and slightly increased RL. Consider that the roughness is not uniform inside the filter, an effective surface conductivity of 0.8×10^7 S/m was used to fit the measured results. Based on this, the resulting Q_u can be calculated as ~5700 using the equations in [20]. It should be noted that, the expected Q_u can be up to 11400, if the filter is plated with silver and the Ra is further reduced (effective conductivity $=3 \times 10^7$ S/m reported in [18]), and the corresponding IL can be reduced to 0.15-0.2dB.

III. SENSITIVITY ANALYSIS OF THE FILTER

To further demonstrate low sensitive to fabrication tolerance of the filter design, another filter with identical specifications but using spherical resonators with tuning posts was employed for comparison. The configuration of the filter is shown in Fig. 5. The tolerance sensitivity analysis is based on Monte Carlo sampling (MCS) method [27]-[28] which is a general method to test robustness of the design with respect to the fabrication tolerance. The proposed filter (dimpled ellipsoid resonator filter) has 12 parameters, including 4 dimples and 8 resonator dimensions. The filter with tuning posts has 20 parameters, including 12 tuning posts and 8 resonator dimensions. The tolerance of the printing is ± 50 µm (resolution of the 3D printer). 400 simulation samples with uniformly random distributed dimensions are performed for each filter. The simulation curves for each filter are shown in Fig. 6. As expected, the proposed filter is less sensitive to the manufacturing tolerance than the filter using conventional posts, in terms of the minimum return loss within the passband: min(RL), maximum bandwidth change: max(ΔBW), and maximum center frequency shift: max(Δf_0). The comparison between two filters are summarized in Table I. It can be observed that the proposed filter demonstrates superior performance in all three indicators.

IV. CONCLUSION

In this letter, for the first time, dimpled ellipsoid dual-mode resonator which is mechanically compatible with the SLM 3D printing process is used to the design of high order dual mode filters. The design is demonstrated to be less sensitive to fabrication imperfections, showing that the use of irregular electromagnetic structures (enabled by 3-D printing) can not only enhance the RF performance of waveguide filters, but also reduce their sensitivity to the manufacturing errors. As a design example, an 8th order dual-mode waveguide cavity was presented and compared with other related works listed in Table II. It can be noted that the proposed filter design offers excellent performance (with no tuning), despite the printing accuracy and surface quality of the SLM process used in this work is in general inferior to the SLA used for some other filters. The proposed filter could be useful in terms of reducing the manufacturing cost without the penalty of worsening the performance.

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