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# THz Letters

## Compact Triangular-Cavity Singlet-Based Filters in Stackable Multi-Layer Technologies

Chad Bartlett, Mohammad Mehrabi, Oleksandr Glubokov, Joachim Oberhammer, and Michael Höft

**Abstract**—In this letter, triangular-cavity bandpass filters are investigated in stackable multi-layer technologies in order to achieve highly compact designs with reduced fabrication complexity. The triangular-shaped cavities are first introduced in the form of singlets and then expanded on as a novel method for achieving a quasi-triplet filter response, where the filter's input and output irises are utilized as resonating means for two additional passband poles. Exploitation of this advanced singlet scheme exemplifies innovative use of resonant irises for achieving highly compact filters that can be manufactured with simple multi-layer fabrication steps for use in future terahertz applications.

**Index Terms**—Deep-reactive ion etching, electrical-discharge machining, resonant iris, singlet, triangular cavity, wire erosion

### I. INTRODUCTION

As trends for high-frequency applications rise, technologies must evolve to sustain current demands as well as prepare for future ones. For the next generation of satellite communications, radar and deep-space exploration, filter designs must be continuously adapted to optimize performance while the allocation of frequency bands reaches beyond the radio-frequency spectrum. Although, different technologies such as high-precision milling [1], SU-8 [2], silicon micro-machining [3] and structured glass [4] have been able to demonstrate the ability to reach well into the terahertz and sub-terahertz regions, progressive design solutions must be continuously explored to coincide with technological advancements.

In order to facilitate future demands for the aforementioned applications, novel designs must be considered for very high-frequency regions where the effect of dimensional tolerances becomes critical, the ability to tune circuits diminishes, and the constraints imposed on size and weight become highly consequential. In the case of compact high-frequency designs, research conducted, such as [3] [5], [6], have been able to demonstrate the ability to minimize the overall footprint of structures, remove the need for lengthy input/output feeding transitions, and in some cases, employ resonant irises to enhance the filter response. Moreover, the introduction of filters with singlets have gained much attention in the literature

due to their relatively small size, simple design, and their ability to easily control transmission zero locations [7]–[9]. Extension of this concept to a variety of different resonator types and filtering operations are exemplified in papers such as [10]–[16].

In regards to simple manufacturing procedures for millimetre and sub-millimetre wave filter components, stackable technologies and multi-layer designs have been demonstrated using methods such as electronic-band-gap (EBG) [17], dif-

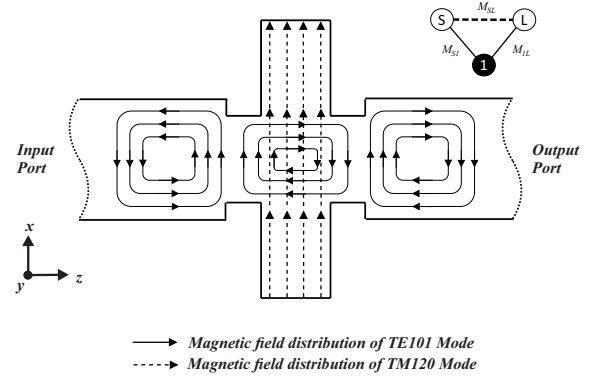


Fig. 1. Magnetic field distribution of Singlet 1 with depiction of the bypass coupling through the triangular cavity. Filter topology; source/load nodes are white and the resonating node is black. Solid lines are the main path while the dashed line is the bypass path.

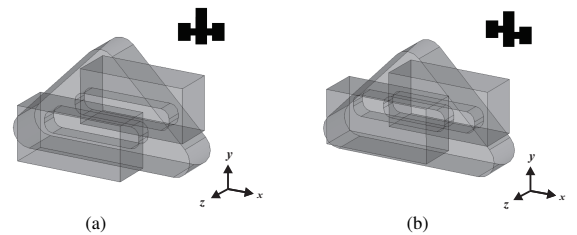


Fig. 2. Vacuum shell of (a) Singlet 1, (b) Singlet 2; The inset images depict the side views of each singlet's input positions, either inline or offset.

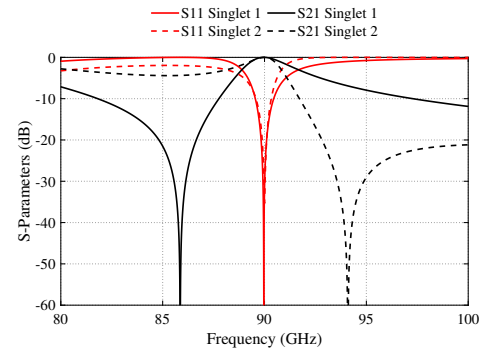


Fig. 3. Simulated results of Singlet 1 and Singlet 2 from Fig. 2.

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fusion bonding of laminated metal plates [18], deep reactive ion etching (DRIE) [3], [5], and structured-glass waveguide (SGW) components [4]. However, miniaturization methods at the millimetre and sub-millimetre wave bands becomes increasingly difficult due to highly stringent dimensions combined with the need for precise alignment of multiple structural layers. In this letter, we propose a simple and elegant design scheme for compact bandpass filters with three stackable layers using an advanced singlet topology. The formulation utilizes a triangular cavity singlet which is combined with two resonant slot-type irises in order to create a third-order bandpass response with one transmission zero, resulting in a quasi-triplet filter topology. In order to verify the proposed filter scheme, a prototype is demonstrated using electrical-discharge machining (EDM) for W-band (75–110 GHz) operation, while a second prototype is demonstrated in DRIE for J-band (220–330 GHz) operation. Each of the bandpass filter iterations demonstrate a highly compact and simple fabrication scheme that is suitable for future terahertz applications.

## II. FILTER DESIGN

The singlet is a first-order topology that is capable of generating a transmission zero either above or below the frequency location of the pole, where the position of the transmission zero depends on the sign of the bypass coupling. In this regard, the transmission zero can be modelled on the lower side of the stopband when  $M_{sl} < 0$ , and on the upper side of the stopband when  $M_{sl} > 0$ , [16].

Advancements in triangular waveguide structures, such as the analysis provided in [19]–[21], allow for the application of singlet theory to be extended to shapes beyond typical rectangular or circular cavities and formulated for the evolution of triangular-shaped filter structures. As outlined in [19], the resonant frequency of an isosceles triangular cavity can be found from

$$f_{mn} = \frac{1}{2a\sqrt{\mu\epsilon}} \sqrt{m^2 + n^2} \quad (1)$$

where  $m = 0, 1, 2, \dots$ ,  $n = 0, 1, 2, \dots$  and  $m + n \neq 0$ . Using (1), we can characterize triangular-waveguide singlets and quasi-triplets operating with the TM120 mode for the first time in the literature as an alternative geometry – which is also convenient for optimizing on-chip layout – and is capable of achieving an equivalent Q-factor via equation (1) when compared to rectangular or cylindrical cavities that have similar thicknesses and center frequencies, and operate with analogous electromagnetic field distributions (i.e., the TM110 and TM010 modes, respectively).

For the design at hand, we select the TM120 mode and formulate the singlet to be fed with slot-type irises in a position that can simultaneously allow for a bypass coupling to pass from the source to load; Fig. 1 depicts the magnetic field distribution for the 90 GHz triangular singlet example that follows in Fig. 2 (a). Additionally, the singlet topology is indicated in the image for reference. Fig. 2 (a) and (b) depict two cases of a singlet which is designed for operation at 90 GHz where the transmission zero position is selected

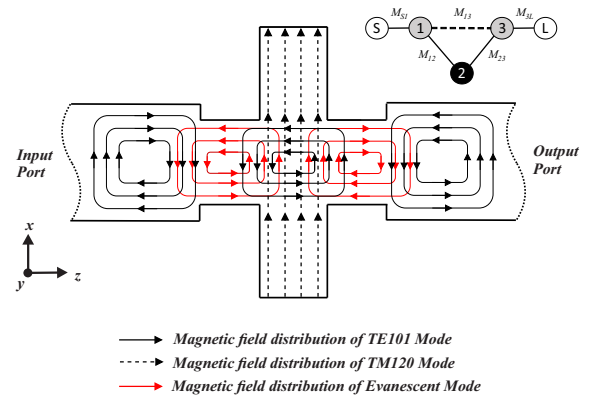


Fig. 4. Magnetic field distribution of the triangular-cavity filter with depiction of the bypass coupling and resonant slot-irises. Filter topology; source/load nodes are white, resonating irises are grey, and the resonating node is black. Solid lines are the main path while the dashed line is the bypass path.

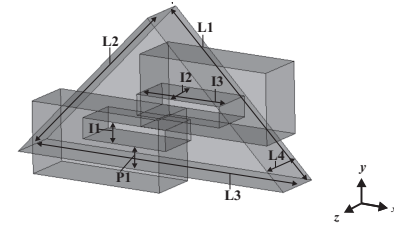


Fig. 5. Vacuum shell of the proposed filter. The corresponding dimensions (in mm) for WR-10: L1=3.800, L2=3.800, L3=5.374, L4=0.900, I1=0.400, I2=0.800, I3=1.660, P1=0.645, and WR-3: L1=1.287, L2=1.287, L3=1.821, L4=0.308, I1=0.117, I2=0.278, I3=0.564, P1=0.234. Values are rounded to three decimal places. An estimated under-etching between 4.25-6.10  $\mu\text{m}$  should be applied to the WR-3 version.

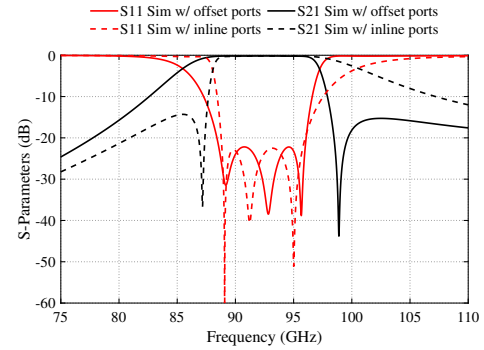


Fig. 6. Simulated demonstration of the transmission zero control when varying the positions of the triangular-cavity filter ports to be inline or offset. The cavity dimensions and resonant slot-irises are optimized for a comparable passband response.

relative to the positions of the source/load coupling; inline or offset. The structure proposed in Fig. 2 (a) results in the transmission zero on the lower side ( $M_{sl} < 0$ ), while the structure proposed in Fig. 2 (b) results in the transmission zero on the upper side ( $M_{sl} > 0$ ). This effect is demonstrated in Fig. 3 for the simulation of each structure over 80 - 100 GHz.

In order to extend this concept to bandpass filter design, the triangular singlet can be modified to include resonant irises similar to the formulations outlined in [22], [23]. Fig. 4 depicts the magnetic field distribution of a singlet with the two resonant irises and describes the basic interaction throughout the filter. The modified topology now includes the resonant

irises and is indicated in the image for reference; it can be noted that the bypass coupling is now formed between the resonant slot-irises (nodes 1 and 3) in a quasi-triplet fashion. The evanescent modes of the resonant slot-irises can be treated as TE<sub>101</sub> modes while the triangular cavity (node 2) utilizes the TM<sub>120</sub> mode. Fig. 5 depicts the vacuum shell of an inline quasi-triplet structure and outlines the dimensions for each of the upcoming prototypes when fed with their respective waveguide ports. Fig. 6 is provided as a demonstration of the transmission zero control when varying the port positions to be inline or offset while the triangular cavity and the resonant irises are optimized for an equivalent passband response.

After the initial design of the cavity from equation (1) for an isosceles cavity, the synthesis of the passband filter can be suitably approximated from the general equations outlined by [24] for external quality factors and synchronous coupling despite the resonant irises and cavity being asynchronous. This method is used as a good approximation, however, the structure can also be viewed in a transverse coupling matrix form for simple parameter extraction. In order to verify this concept, a third-order filter with a FBW and center frequency of approximately 7.2% and 91.7 GHz is specified for EDM wire erosion for WR-10 band operation, while another with a FBW and center frequency of approximately 5.4% and 268.9 GHz is specified for DRIE on silicon-wafers for WR-3 band operation.

### III. FABRICATION AND MEASUREMENTS

For the WR-10 version of the filter, wire-erosion was selected for its ability to reduce the necessary corner radii within the structures. Brass was selected as the cutting material with an erosion wire of 60  $\mu\text{m}$  radius. The filter is fabricated as three individual pieces, namely, brass plates that house the irises and the triangular cavity. For the WR-3 version of the filter, a standard silicon micromachining process based on DRIE has been employed for its ability to obtain micron-level detail and high repeatability. The fabrication has been performed on a silicon-on-insulator (SOI) wafer which consists of a 30  $\mu\text{m}$  device layer, a 275  $\mu\text{m}$  handle layer, and a 3  $\mu\text{m}$  buried oxide layer. The proposed filter was built using three stacked layers while gold (Au) sputtering was used to metallize the chips. Each of the layers are aligned on top of one another using vernier scale alignment marks before thermo-compression bonding. To minimize the effect of under-etching and promote a high accuracy between the simulated and measured results, the middle layer is fabricated using a fallout technique [25], and a compensative side wall under-etching effect has been applied to the design.

Once fabricated and assembled, both versions of the filters were tested using a Rohde & Schwarz ZVA67 with their respective up-converters. Fig. 7 presents the fabricated structure from EDM wire erosion while Fig. 8 presents a comparison of the simulated and measured results over 75 - 110 GHz. The measured return loss is better than 20 dB in the measured passband while the measured insertion loss at the measured center frequency is approximately 0.31 dB with an estimated  $Q_u$  of  $\approx 500$ . Fig. 9 presents the fabricated

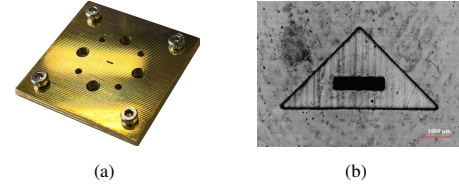


Fig. 7. Fabricated W-band prototype. (a) The assembled filter unit, and (b) Close-up view of the internal cavity and one of the resonating iris-slots.

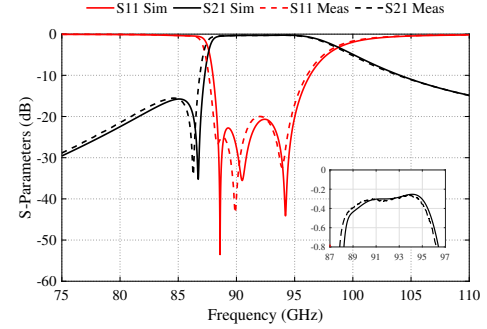


Fig. 8. Simulated versus measured S-parameter results of the stacked EDM filter for W-band operation. Effective conductivity is taken as 7.50 MS/m.

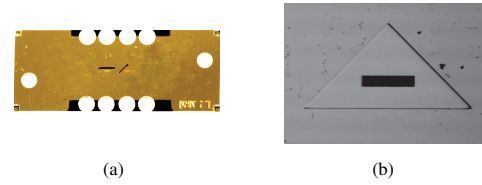


Fig. 9. Fabricated J-band prototype. (a) Chip layers one and two stacked on top of one another with two internal cavities shown, and (b) Close-up view of an internal cavity and one of the resonating iris-slots throughout the chip.

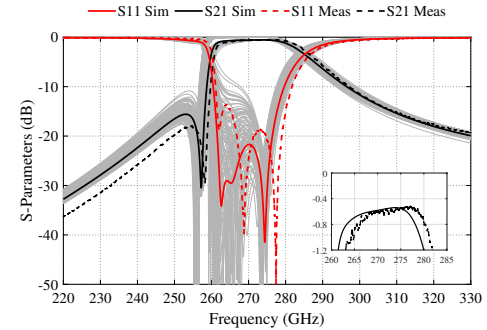


Fig. 10. Simulated versus measured S-parameter results of the stacked silicon-wafer filter for J-band operation. Effective conductivity is taken as 10.8 MS/m. Grey lines indicate the tolerance analysis of 100 runs.

structure from DRIE micromachining while Fig. 10 presents a comparison of the simulated and measured results over 220 - 330 GHz. The measured return loss is better than 13.5 dB in the measured passband and the measured insertion loss at the measured center frequency is approximately 0.61 dB with an estimated  $Q_u$  of  $\approx 300$ . A tolerance analysis comparing 100 runs with Gaussian randomized points within  $\pm 2\mu\text{m}$  is added to the figure. However, some mismatch may be attributed to the under-etching effect caused by deep-reactive ion etching and may be compensated in further iterations. The WR-10 and WR-3 L·W·H internal dimensions are approximately



0.764-1.588-0.814  $\lambda^3$  and 0.864-1.821-0.815  $\lambda^3$ , respectively.

#### IV. CONCLUSION

In this work, the concept of triangular-cavity singlets combined with resonant irises are explored in order to achieve novel bandpass filters in stackable multi-layer technologies. Prototypes of the filter concept are designed and measured for high-frequency applications in the WR-10 and WR-3 bands with wire-erosion and silicon-wafer technology, respectively. The introduction of singlets with slot-type resonant irises demonstrates a versatile approach for compact filter design suitable for future terahertz applications.

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