Rectangular Waveguide Filters Based on Deformed Dual-Mode Cavity Resonators

Michał Baranowski[#], Łukasz Balewski[*], Adam Lamecki[*#], Michał Mrozowski[#]

[#]Department of Microwave and Antenna Engineering,
Faculty of Electronics, Telecommunications and Informatics,
Gdansk University of Technology, Poland

[*]EM Invent Sp. z o.o., Poland

{m.baranowski, adam.lamecki, m.mrozowski}@ieee.org, lukasz.balewski@eminvent.com

***Abstract* — In this paper, a novel design for rectangular waveguide filters with deformed dual-mode (DM) cavity resonators is demonstrated. The new resonant cavity shape is a result of applying shape deformation to the basic rectangular cavity to enable its dual-mode operation. Internal coupling between the two orthogonal cavity modes is realized by geometry deformation, eliminating the need for additional coupling elements. The designs are developed within the constraints of 3-D printing to allow their fabrication in one piece. In addition, the design method used results in models with smooth surfaces, which is highly desirable for high-power and low-loss applications. A deformed DM cavity is analyzed and a single cavity second-order filter is designed and presented. Finally, two types of fourth-order filters with transmission zeros are designed by combining two deformed DM cavities and their performance is verified experimentally by a 3D-printed prototype.**

***Keywords* — Dual-mode waveguide filters, design optimization, shape deformation, additive manufacturing.**

I. Introduction

In recent years, additive manufacturing (AM) has received a lot of attention as one of the emerging technologies for efficient manufacturing of passive microwave components such as waveguide filters, couplers and antennas [1], [2], [3], [4], [5]. One of the primary benefits of 3-D printing for the creation of high-frequency electronics is its low production cost and huge flexibility in achieving complicated 3-D models. The flexibility in printing structures of nearly any forms might alleviate the restrictions of well-established methods such as CNC milling, enabling new potential in microwave component design. Novel 3-D-printed components may benefit from non-standard, custom shapes, resulting in superior electromagnetic (EM) performance, such as higher quality factor Q, better spurious mode separation of microwave filters [6], or higher power handling capability. However, to make good use of the potential offered by AM, a microwave engineer needs to have access to suitable design tools which would allow efficient modeling and EM simulation of 3-D structures with truly arbitrary geometries. One possible solution is the development of new design methods, such as the recently introduced synthesis of waveguide filters with smooth profile oriented toward direct metal 3-D printing [7]. Another possibility is to provide more degrees of freedom for 3-D modelling by extending the capabilities of conventional EM computer-aided design (CAD) tools. Such an approach was presented in [8] by introducing shape deformation techniques to 3-D CAD of high-frequency passive components. To provide a highly efficient semi-automated shape optimization [9], a free-form geometry modification algorithm based on radial basis function (RBF) interpolation was developed and integrated with a 3-D finite element method (FEM) in the EM field simulator InventSim [10].

In this work, the aforementioned shape deformation strategy is applied to the design of smooth-profile rectangular waveguide DM cavity filters for one-piece fabrication by direct metal AM. To date, several designs of DM filters manufactured by 3-D printing were reported in the literature, such as the design based on ellipsoidal cavity, where the two orthogonal cavity modes are excited by the rotation of the input and output ports [11]. A similar cavity shape and coupling scheme is also realized in the design of dual-band DM filters [12]. These designs particularly benefit from AM because spherical or ellipsoidal cavity shapes are difficult to produce using conventional subtractive methods. The designs presented in this paper will also take advantage of having complex geometry which could not be manufactured by methods other than 3-D printing. Our design builds on rectangular cavities, and in this regard it resembles low-cost DM filters based on rectangular waveguide reported in [13] and [14]. In [13], the dual-mode operation is based on the use of the TEm0n mode family (corresponding to the horizontal dimensions of the rectangular cavity) and the designs were manufactured using traditional CNC milling. Alternative rectangular DM cavity design operating with two diagonal modes reported in [14] achieves dual-mode operation by rotating an almost square waveguide cavity by $45°$ and introducing a perturbation of its dimensions to couple both modes. In our work, the second cavity mode is excited along the vertical direction, the shape of the cavity is modified to obtain non-homogeneous cross-section, and the filters are prepared for low-cost fabrication by 3-D printing in one piece.

II. Resonant Cavity Analysis

The starting point for this work is a smooth-profile rectangular waveguide cavity [9], shown in Fig. 1a. The cavity operates with the fundamental TE101 mode and thus produces

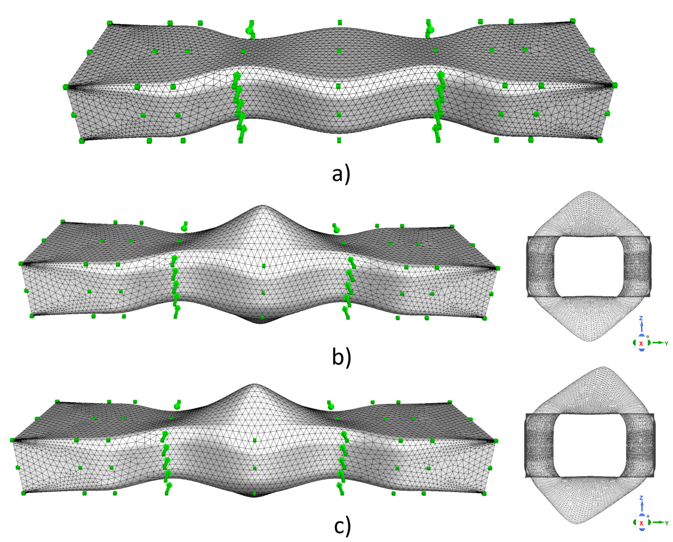

Fig. 1. Geometry of the resonant cavity: a) basic smooth-profile rectangular cavity, b) vertically stretched cavity and its front view, c) modified cavity with introduced horizontal offset and its front view.

a single transmission pole, as shown in Fig. 2 (dotted line). The cavity has a constant height and deformed side walls. To achieve dual-mode operation we modify its shape by applying vertical stretching (along the Z-axis), as shown in Fig. 1b. However, such a deformation will not create an additional transmission pole as the symmetry of the cavity is maintained and the second degenerate mode is not excited (see Fig. 2). Coupling screws could be introduced to excite the second mode, but this would reduce the Q-factor of the cavity and add to the complexity of the design. Instead, the two modes can be excited by introducing a non-zero horizontal displacement (in the Y-axis direction) into the defined stretching operation, as shown in Fig. 1c. As the symmetry is now broken, the mode

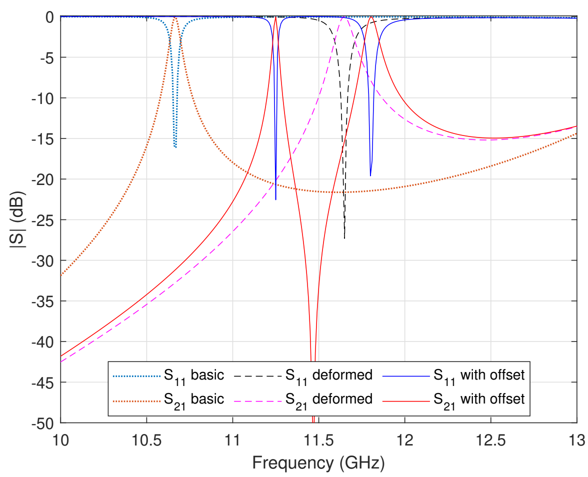

Fig. 2. Simulation results for different cavity shapes: dotted line - basic cavity (Fig. 1a), dashed line - vertically stretched cavity with symmetry (Fig. 1b), solid line - vertically stretched cavity with horizontal deformation offset (Fig. 1c).

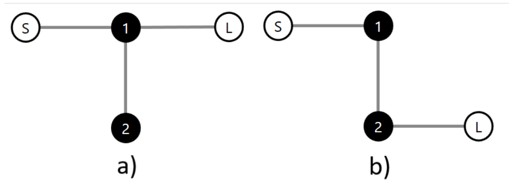

Fig. 3. Coupling-routing diagram of the modified single-cavity DM filter: a) with input and output in agreement, as shown in Fig. 1c, b) with a 90-degree rotation of the output.

degeneracy is removed. This results in two transmission poles, separated by a transmission zero (TZ), as shown in Fig. 2 (solid line). Such a DM cavity arrangement with input and output waveguide ports oriented horizontally corresponds to the coupling-routing diagram (CRD) shown in Fig. 3a. In this configuration, the source and load are coupled to one of two orthogonal modes supported by the cavity. An alternative inline CRD, shown in Fig. 3b, is obtained when the output port is rotated 90 degrees with respect to the input. This is because the input is coupled to the first mode, and the output is coupled to the second (orthogonal) mode. In all designs presented, the input/output (I/O) coupling is realized by inductive irises, formed by squeezing the waveguide sidewalls (marked with green arrows in Fig. 1). With a 90° rotated output and a single DM cavity a second-order filter is obtained, generating a two-pole response, as shown in Fig. 4 with center frequency CF = 11.5 GHz and a 200 MHz bandwidth. The cavity shape and its front view for such a configuration is presented in Fig. 5. EM simulations show that the unloaded Q of the cavity for aluminum ($\sigma = 3.8 \cdot 10^7$ S/m) is equal to 9500 for one mode and 9250 for its degenerate counterpart. Such a modified DM cavity design can work as a smooth-profile, high-Q second-order filter with 90° twisted output, and can also be used as a building block for higher-order filter configurations.

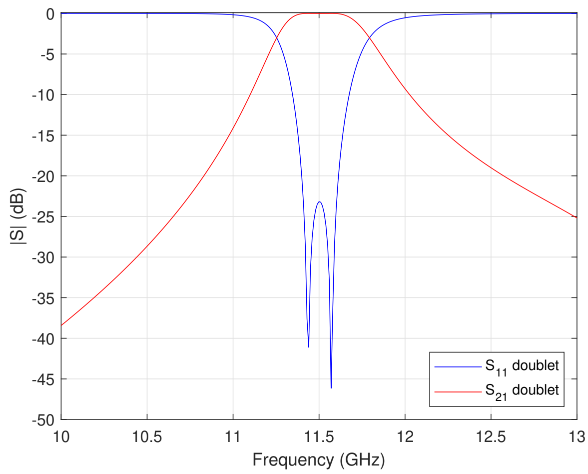

Fig. 4. Simulation results for a single-cavity DM filter from Fig. 5.

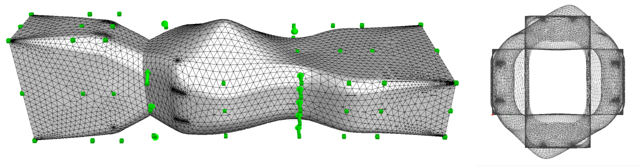

Fig. 5. Geometry of the modified single-cavity DM filter and its front view.

III. Design of Dual-Mode Cavity Filters

A. Filter Design

The proposed DM cavities were used to design a fourth-order filter with a smooth profile in a quadruplet configuration. The deformation operations and final filter geometries are presented in Fig. 6. The filter consists of two DM cavities, coupled via a quasi-square iris and connected to a standard WR-75 waveguide at the input and output. Depending on the orientation of the output port, two different quadruplet configurations can be achieved. The first design, with the I/O ports in alignment, as shown in Fig. 6b, produces four transmission poles and two TZs. This design corresponds to the coupling-routing scheme in Fig. 7a. The second design, with a

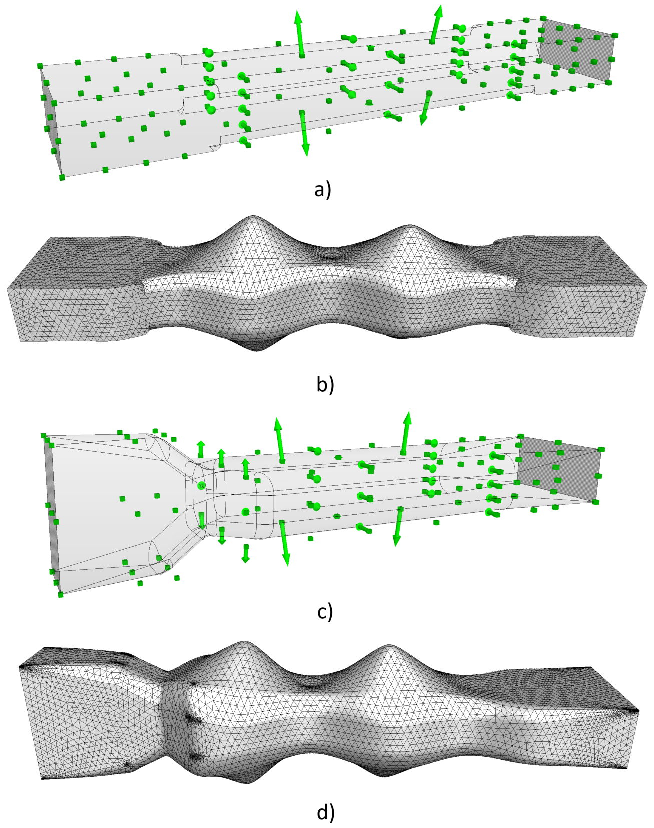

Fig. 6. Geometry of the fourth-order DM cavity filters: a) base structure with shape deformation indicated by green arrows and fixed (non-movable) points denoted by green points, b) fourth-order DM cavity filter with input and output ports in alignment, c) shape deformation definition for the alternative 90° rotated output configuration, d) fourth-order DM cavity filter with a 90° output rotation.

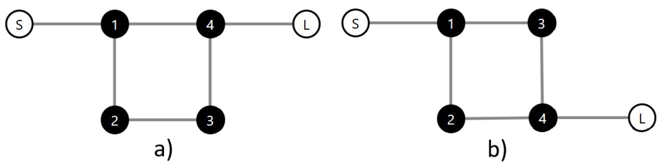

Fig. 7. Coupling-routing diagram of the fourth-order DM cavity filter configurations: a) with input and output in agreement, as in Fig. 6b, b) with a 90° rotation of the output, as in Fig. 6d.

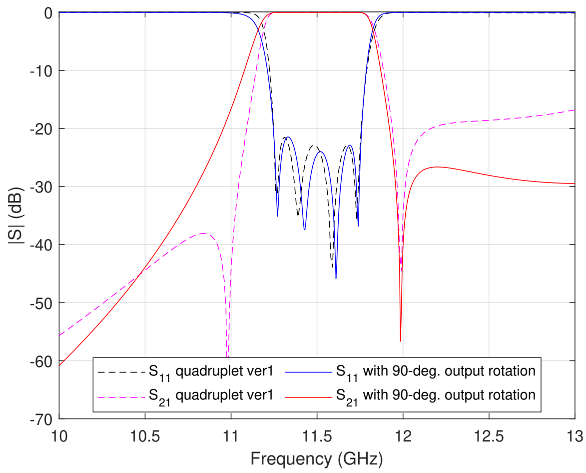

Fig. 8. Simulation results for two quadruplet designs using deformed DM cavities: dashed line - fourth-order filter with two TZs from Fig. 6b, solid line - fourth-order filter with one TZ and a 90-degree output rotation from Fig. 6d.

90° rotated output, as in Fig. 6d, produces a four-pole response and one TZ, and its CRD is shown in Fig. 7b. The design specifications for both versions are as follows: the center frequency CF = 11.5 GHz, the bandwidth BW = 500 MHz and the in-band return loss RL $>$ 20 dB. One TZ is positioned at 12 GHz and the other, in case of the non-rotated version, is centered at 11 GHz. The designs were optimized in InventSim [10] by altering the deformation parameters controlling the shape of the cavities and coupling irises. The zero-pole method was used as the optimization technique [15], [16], [17]. The comparison of the EM-simulated results for both optimized designs is provided in Fig. 8. It should be noted that although the rotated configuration produces only one TZ, it has a better upper stopband rejection level than the straight quadruplet design, and thus may be of greater practical use. Based on EM simulation for aluminium, the in-band insertion loss is in the range 0.06-0.11 dB, while the estimated Q-factor of the filters is equal to 6700 and 6500 for the straight and rotated designs, respectively.

B. Fabrication and Measurement

The fourth-order filter design with rotated output was prepared for fabrication and 3D-printed in one piece with aluminum alloy (AlSi10Mg) using selective laser melting (SLM) technology. The fabricated component was measured and the results were compared with EM simulation. As shown in Fig. 9, a very good agreement with the simulated model

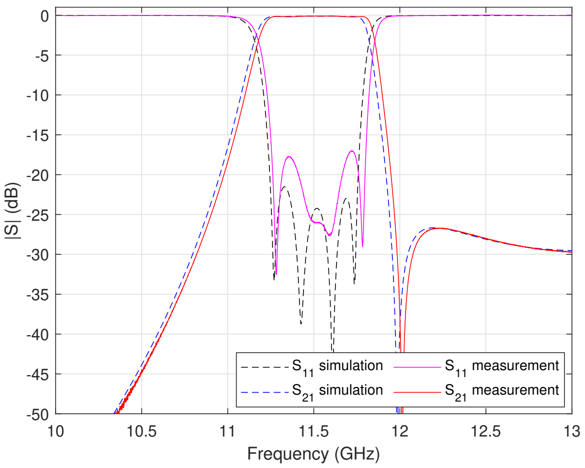

Fig. 9. Measurement results of the fabricated fourth-order filter with one TZ and a 90-degree output rotation from Fig. 6d: dashed line - EM simulation, solid line - measurement.

was achieved. The passband is shifted ca. 40 MHz above the specified band and the in-band RL level is 17 dB, which could be corrected by tuning screws. The insertion loss at CF is 0.11 dB, which results in estimated Q-factor of ca. 3500. To achieve a better effective conductivity and obtain a higher Q-factor, the surface of the filter could be polished or silver plated. Nonetheless, the fabricated component validates this filter design based on deformed DM cavities and the design approach using smooth geometry deformation.

IV. Conclusion

This paper presented a new rectangular waveguide dual-mode cavity with a smooth surface profile. The new cavity model was designed using shape deformation and is compliant with 3-D printing so it could benefit from complex geometry which would not be feasible to manufacture with subtractive methods. Geometry deformation enables the dual-mode operation by breaking the symmetry of the cavity and thus coupling the two degenerate modes together. A single-cavity second-order filter and two types of fourth-order filters with transmission zeros were designed and one of the fourth-order filters was fabricated through 3D printing as an experimental validation of the concept. Future research may focus on further investigation of this type of DM cavities, including the design of higher-order filter configurations and research into potential improvements in out-of-band rejection level.

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