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Development of Substrate Integrated Waveguide filters for low-cost high-density RF and microwave circuit integration: Pseudo-elliptic dual mode cavity band-pass filters

Yu Tang [a], Ke Wu [a], Nazih Khaddaj Mallat [b,*]

[a] Poly-Grames Research Center, Ecole Polytechnique de Montréal, Montréal, Canada
[b] College of Engineering & Information Technology, Al Ain University of Science and Technology, Al Ain, United Arab Emirates

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ABSTRACT

The properties of dual mode resonance in planar SIW-based rectangular cavities are investigated and discussed. A specific mode combination of dual mode cavity presents a unique frequency response feature. With the aid of an optimization process or software, it is convenient to cascade a number of cavities with coupling apertures to form a filter. A 3-cavity pseudo-elliptic SIW filter based on H_{203} & H_{104} hybrid resonance is designed and fabricated on a Rogers TMM3 substrate. Measured results show that the insertion loss at the central frequency around 24 GHz is 4.58 dB and the return loss is better than 20 dB in the whole pass-band of 760 MHz. The design method can widely be used for high-density microwave integrated circuits and the mass-fabrication of such filters is made easy even when keeping development and processing costs very low.

1. Introduction

Current trends in the development of RF and microwave circuits covering millimeter-wave ranges are generally oriented towards a low-cost and high-density integration of RF and microwave circuits and systems. This is now mainly driven, in particular, by the invention and development of the concept of Substrate Integrated Circuits (SICs) including the Substrate Integrated Waveguide (SIW), which allows the design of usually three-dimensional waveguide circuits in planar form, thus making possible a complete integration of planar and non-planar structures made of a single substrate through a single process of fabrication. In particular, the SIW technique has been found attractive in the design of high-quality passive components such as filters and antennas. The achievement of SIW filters structures, including power capability and thermal effect, in practical design is summarized in [1–3]. Recently, varieties of topologies are used by different authors to develop SIW filters. If the modes in the confined waveguide structure are of the boundary condition of TE mode, the cavity or filtering structure can be realized in SIW. In TE modes, there is no current flow in x and y direction on the side walls (z is the normal direction to the SIW plane). Regarding the dual mode realization of filter in waveguide structure, there are some previous structures which can be implemented with 2D SIW technique. For example, [4] used corner cut to produce dual mode. The early years' efforts to develop SIW filter, mainly used rectangular cavity. Later in 2007, circular cavity SIW was also used [5].

The work described in this paper represents the second part of a filter project using SIW technique. The first part, where a number of design features and modeling strategies have been presented and discussed for direct-coupled single mode cavity filter developments, was published last year [6], and this is the second part about dual mode realization. These filters (both single and dual mode) were one of the earliest batches of SIW filters associated with the specifications and the filter responses through sophisticated design procedure and consideration. In this paper, the work is devoted to investigate the basic characteristics of rectangular dual mode cavity in various mode combinations for a better understanding of their deployment in the filter developments. The tuning properties of the H_{203} & H_{104} cavity, for example, are examined in detail. On this basis, filters with two cavities and three cavities were designed in a full-wave simulation environment.

2. Cross coupling and dual-mode resonance in waveguide

The filters designed by a full-wave simulation method on the basis of dual mode rectangular cavities are presented in this work.

* Corresponding author.
E-mail address: nazih.mallat@aau.ac.ae (N. Khaddaj Mallat).

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The development of the filters makes use of a dual mode resonance in a rectangular waveguide proposed in [7,8]. The discontinuities formed by the apertures between the waveguide input/output port and the cavity, and the aperture between the cavities, may be numerically analyzed on the basis of a multi-mode network representation. Therefore, the coupling coefficients between modes can be calculated. They are represented as a function of geometric parameters. The required dimensional parameters of the proposed filtering structure in [7] may be obtained by the application of conventional approaches, as described in [12], where the coupling coefficient is calculated through a method of electric polarizability [9–12]. Dual mode cavity filters show an insertion loss lower than the counterparts built on single mode resonators; this gives its predominance regarding the application to the design of SIW filters. In this paper, the full-wave simulation tool – Ansoft HFSS is directly used for such filter design and developments.

The feasibility of employing some rectangular dual mode combinations is demonstrated after introducing the dual mode resonance mechanism in Section 3. Next, the coupling scenario and the designed filters employing rectangular $H_{203}\,\&\,H_{104}$ dual mode combinations are demonstrated in Section 4. The measurement results are shown in Section 5.

SIW structure can be formed either by two rows of closely placed via holes or by two groups of slots. In the first type of SIW structure, there is a relationship between the width of a pure metal wall guide (filled with dielectric) and their equivalent width for corresponding via hole SIW guide. Indeed, there is some slight radiation (leakage) through the gap between via holes. In this paper, instead of via holes, long slots are used to keep the metal walls where their fields are apparently strong. This may avoid radiation from the gaps between via holes. The slots are interrupted only at the weak field corners, where the field is approaching to zero and reverses their direction. The long slot formed SIW guide width is exactly the same as the pure metal wall guide.

2.1. General synthesis theory

A general synthesis theory was developed by Atia and Williams [13–17]. Mutual couplings between cavities are indicated as M_{ij}. The synthesis of band-pass filters is most conveniently achieved by assuming a symmetric network, and that matrix M is symmetrical about its main diagonal. In the general synthesis theory, coupling between non-adjacent cavities produces transmission zeros (TZs) in the stop-band. A typical synthesis procedure is described in [12] for a four-cavity elliptic waveguide filter.

2.2. The realization of finite transmission zero of filters

The theory of synthesis devises a method which considers all the possible mutual couplings between cavities. However, the synthesized coupling matrix is not always able in practice to be realized in physical terms. In this section, a few physical realizations which were adopted to improve filter properties are listed. Some were based on the general synthesis theory and others were designed using a range of methods. The purpose of these examples is to show the required principles.

2.2.1. Direct-coupled cavity single mode filter

Three-resonator filters with extra coupling K_{13} between resonators 1 and 3 were chosen [18]. The bridging coupling K_{13} was used as an inductive circular iris on a thin metallic plate. The frequency response of this filter produces a band reject behavior on one filter skirt. In order to produce a band reject behavior on both filter skirts, a general four-resonator filter is employed in a coaxial cavity [18]. The bridging coupling K_{14} holds the opposite sign with reference to the normal couplings (K_{12}, K_{23}), providing a phase reversal in the cross-coupling results in TZs in the stop-band of the filters.

A filter prototype implementing TZs at finite frequencies, with a view to equalizing the time delay, was introduced by Rhodes [20]. Rhodes presented the prototype of a filter formed by two parallel direct-coupled waveguide filters, in which adjacent cavities were cross-coupled via their common narrow wall, to generate TZs.

A structure similar to that in [18] was described in [21], where the side wall circular aperture is replaced by a square aperture with the same height of the cavity. With the same mechanism as that for producing TZs, a folded E-plane metal insert filter was realized in [22].

2.2.2. Dual-mode waveguide cavity filter

Reversing the phases between the coupled non-adjacent cavities, so as to produce negative coupling K_{14}, can be undertaken in dual mode waveguide structures. The filter, as reported by Williams in [12], with four pole and two TZs is realized with circular waveguide H_{111} – mode circular cavities.

In the filter structure, a coupling screw is put at an orientation of 45° to the normal field polarization. The incident wave in the first cavity is split into mode 1 and mode 2 of H_{111}, which produces M_{12}. In the second cavity, a coupling screw splits the field into two degenerate modes 3 and 4. The spatial orientations 90° apart give a field reversal of 180°, producing $M_{14} < 0$. It is demonstrated that the general form of the band-pass transfer functions of a symmetrical network can be realized in either single- or dual-mode coupled-waveguide cavities. The filter realization in a rectangular waveguide dual-mode cavity was also reported [16], where a sixth-order elliptic response with four TZs from a rectangular-cavity dual-mode waveguide is obtained.

3. Rectangular waveguide dual-mode filter

Being restricted by the coupling scenario in the SIW cavity, two types of topology may meet the requirements of a rectangular dual-mode cavity filter. If the coupling aperture is put on the broad wall of a rectangular cavity, multiple layer substrates must be used. If the coupling aperture is placed only on the end and side walls of the rectangular waveguide, the component can be fabricated on one layer of substrate.

As known, the single mode resonator filter is considered as the main reference point for advancing to its dual mode design counterpart. Conventional single mode resonator filter and many other designs [19–22] present single-mode filters in which each resonator provides one transmission pole, and where higher order mode interactions are used to implement transmission zeros to improve the filter's selectivity. [7] proposes a new family of all-inductive dual-mode scenario, where each cavity of the filtering structure produces two transmission poles and at least one transmission zero, and the all-inductive coupling of the inter-cavity allows a simple planar dual-mode filter on substrate to be implemented.

3.1. Tuning properties of the $H_{203}\,\&\,H_{104}$ cavity

A detailed investigation of the single $H_{203}\,\&\,H_{104}$ cavity is carried out in a full-wave electromagnetic simulation environment. An alumina ceramic substrate with a permittivity of 9.9 and a thickness of 10 mil is employed. The filtering structure consists of three parts: resonant cavity, coupling apertures, and waveguide input/output port. The point of origin of the axis is set at the center of