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Xiaobang Shang, Michael J. Lancaster and Stefan Dimov

An investigation into rectangular waveguide filters with open slots on the broad side walls is reported. This type of waveguide filter eliminates the need for direct contact between the two waveguide halves and intentionally leaves a gap in the middle of broad side walls. For X-band (8.2 - 12.4 GHz) waveguides, such a gap can be nearly as wide as 9% of the internal waveguide width *a*, without introducing any significant radiation loss. A 5th order filter centred at 10 GHz with a fractional bandwidth of 2% is designed based on such a structure, and fabricated from aluminium and tested. There is a good agreement between measurement and simulation results. This verifies the proposed structure as well as the design procedure.

Introduction: Waveguide filters have been widely used in communication and radar systems to select signals with desired frequencies and attenuate the unwanted. Usually, waveguide filters are constructed from two or more pieces to facilitate the fabrication process. These pieces are assembled together, commonly using many bolts, to form a complete filter. The quality of the joints can have a significant impact on the waveguide filter's performance [1]. Good joints become even more vital for waveguide filters operating at submillimetre-wave and terahertz frequencies, as in such case bolts can no longer be utilised due to the small size of waveguides. In addition there are recent attempts in making metal coated polymer filters [2-3] and here to achieve a good joint becomes even more difficult. Efforts have been made to address the problem of joining and several design configurations have been proposed to relief the strict requirement of a good joint, for instance the photonic crystal joint features reported in [4]. Here it is also suggested an E-plane split, as illustrated in Fig. 1*a*, which will provide the best insertion loss performance as current does not flow across the joints. This is a well-known method of reducing the negative effects of joints. Additionally, efforts have been made on substrate integrated waveguide (SIW) to rely on only half of the conventional filter to achieve the filter functionality [5]. Such half mode SIW filters are more compact in size and have an improved upper out-of-band rejection [5]. However, considerable loss due to leakage and dielectric may prevent the application of such SIW structures at terahertz frequencies.

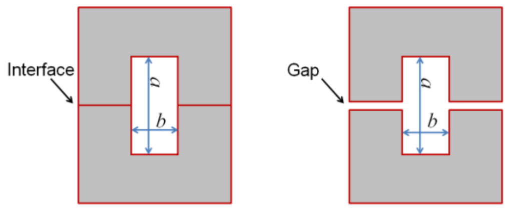

Fig. 1 *Illustration of E-plane split waveguide.*
a Conventional arrangement
b Arrangement proposed here.

Here we focus on rectangular waveguides and propose a design without any joints and instead having a gap between two waveguide halves. This is shown in Fig. 1*b*. This reduces the difficulties associated with joining operation, while at the same does not have the penalty of degraded insertion loss. However, such a gap has an impact on the resonator's resonant frequency as the effective length of the resonator has been changed. By factoring in the effect of a gap during the filter design, it is feasible to achieve a filter with excellent insertion loss (the same as that of a conventional filter with good joints). Here this is demonstrated by an X-band waveguide filter with 2 mm wide slots at the centre of the broad side walls. The filter exhibits an insertion loss very close to simulated and theoretical values.

Investigation into a waveguide resonator with slots: In order to understand the impact of slots on microwave performance, an X-band resonator with slots on two broad side walls (Fig. 2*a*) is considered first. It is weakly coupled to external ports through small capacitive irises. CST [6] simulations are performed for six different slot widths *g* ranging from 2 to 7 mm. Their corresponding quality factors *Q* and resonant frequencies can be extracted from simulation results [7] and are given in Fig. 2*b* and Fig. 2*c*, respectively. In case *g* equals to 0 (i.e. no slots), *Q* is calculated from simulation results to be 43305 and the resonant frequency f_c is 10 GHz. This *Q* is the external quality factor Q_e, as PEC does not contribute to any conductor loss. For all the above simulations, the external quality factor Q_e is about 43305 as the capacitive iris size remains constant. Since all the *Q* values shown in Fig. 2*b* are smaller than Q_e, hence they can be mainly attributed to the radiation quality factor Q_r. As can be observed in Fig. 2 Q_r reduces and f_c increases with the increase of slot width *g*. Additionally, it can be found from Fig. 2 that Q_r and f_c are relatively independent of waveguide wall thickness *t*. In this work 2 mm is chosen as the waveguide wall thickness. The *Q* of a TE_{101} waveguide cavity (without dielectric filling) due to conducting loss can be calculated as [8]

$$Q_c = \frac{(kad)^3 b\eta}{2\pi^2 R_s} \frac{1}{(2a^3b + 2bd^3 + a^3d + ad^3)} \tag{1}$$

Where R_s is the surface resistivity of the metallic walls, *d* is the length of the resonator, η is the intrinsic impedance and *k* is the wave number. For a TE_{101} cavity made from aluminium with a resonant frequency of 10 GHz, Q_c is calculated to be approximately 6367 using (1). As shown in Fig. 2*b*, Q_r is 31363 for *g*=2 mm and 4200 (smaller than Q_c) for *g*=3 mm. Hence 2 mm is chosen as the slot width for the filter discussed in the following section such that Q_c<<Q_r.

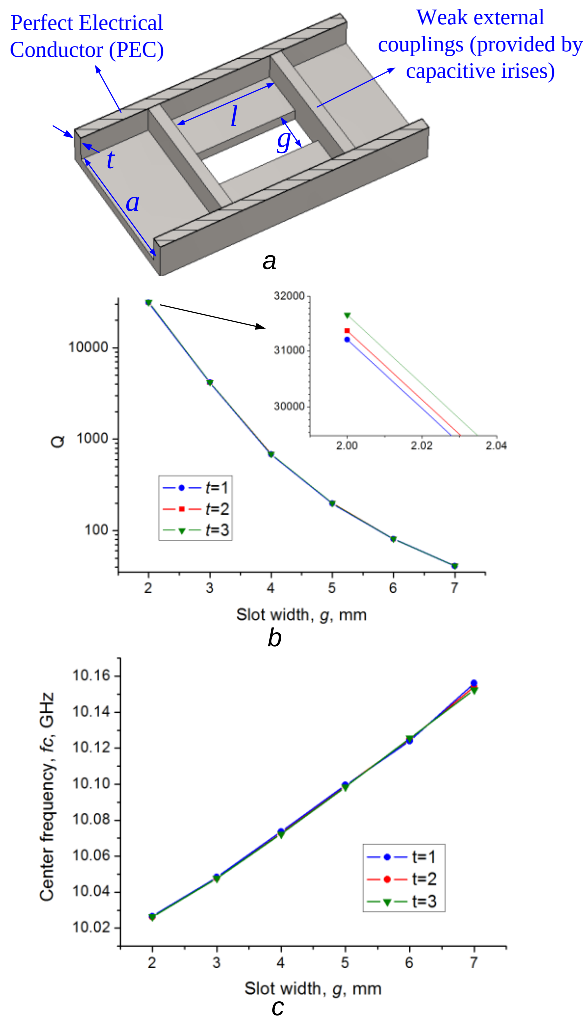

Fig. 2 *An X-band TE_{101} cavity resonator with broadside wall slots.*
a Configuration of the resonator which is weakly coupled through two capacitive irises. Slot width *g* and waveguide wall thickness *t* are altered in the simulations. *a*=22.86, *l*=19.902, *t*=2. Unit: mm.
b Simulation results of *Q* for the structure in Fig. 2*a*.
c Simulation results of resonant frequency for the structure in Fig. 2*a*.

X-band 5th order filter: a 5th order X-band filter centred at 10 GHz with a fractional bandwidth (FBW) of 2% is designed using the structure with slots. This filter is designed to have Chebyshev responses with a passband return loss of 20 dB. Its corresponding external Q and internal coupling coefficients are calculated to be [7]: $Q_{e1}=Q_{e5}=48.57$, $m_{12}=m_{45}=0.0173$, $m_{23}=m_{34}=0.0127$. Accurate physical dimensions can be obtained from these coupling coefficients by following the procedure given in [7]. Note that, 2 mm wide slots are included in all simulated structures used to extract physical dimensions. Resonator lengths and coupling irises are altered to compensate for the slots' impact. Fig. 3 shows a top view diagram of the filter and its dimensions. This filter's corresponding simulation results are shown in Fig. 5.

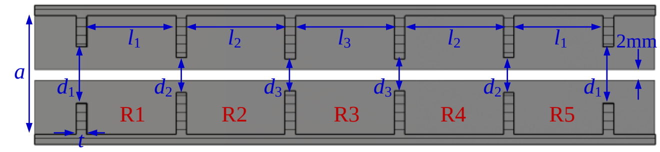

Fig. 3 *Configuration of the X-band filter and its dimensions.*

Five resonators are operating at TE_{101} mode and are denoted as R1-R5 in the figure. These resonators are coupled through symmetrical inductive irises which have the same thickness t of 2 mm. a=22.86, d_1=10.827, d_2=6.733, d_3=6.109, l_1=17.135, l_2=18.853, l_3=19.003. Unit: mm. All inner corners have the same radius of 1.6 mm.

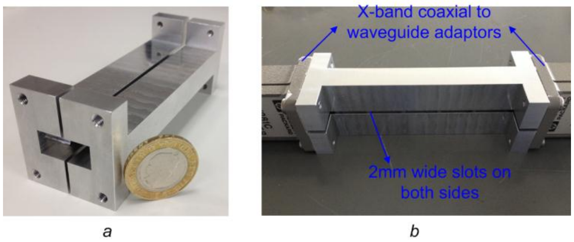

Fig. 4 *Photograph of the fabricated X-band filter.*
a Photograph of the filter which is formed of two identical pieces.
b Photograph of the measurement setup.

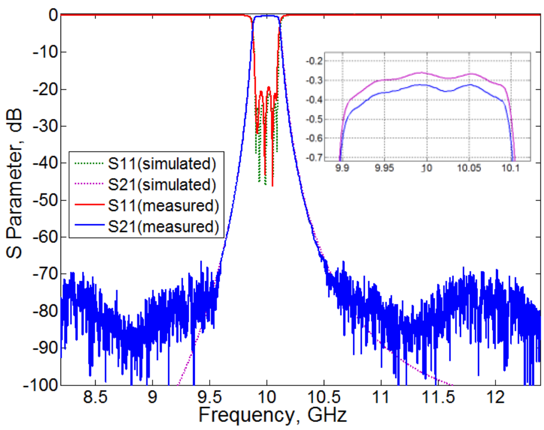

Fig. 5 *Measurement (solid lines) and simulation (dashed lines) results of the filter. The insert shows enlarged view of the filter responses over passband. No tuning screws have been used in the measurements.*

Experimental verification: The filter is machined from aluminium and a photograph of the filter is shown in Fig. 4*a*. During the measurements, the two pieces of filter are sandwiched between the flanges of the network analyser, as shown in Fig. 4*b*. The bolts which attach the flange are used to align the filter to the flanges as well as to provide an intimate contact between them. Before tightening screws, a feeler gauge is used to ensure the gap between the two pieces is constant and uniform. Fig. 5 depicts the measurement results which agree well with the simulations. The average passband insertion loss is measured to be around 0.35 dB, which is 0.05 dB higher than the value obtained from CST simulations using the conductivity of aluminium. It is believed that this small difference may be attributed to a combination of the following factors (i) worse-than-simulated return loss (the measured return loss is around 1 dB higher than the simulation results and this leads to an additional insertion loss of 0.011 dB); (ii) small calibration and simulation errors; (iii) non-perfect surface quality (e.g. surface roughness), introduced during the milling process, which degrades the effective conductivity of aluminium. According to CST simulations, for a conventional filter with the same specifications but no slots, its insertion loss is nearly the same as that of the filter with slots (shown in Fig. 4). Objects surrounding the filter do not have a noticeable impact on the filter's performance, since the radiation energy is extremely small. Different packaging materials (e.g. metal and polymers) can be used around the filter to protect it from liquids and any airborne dust. Although in this work the filter is formed of two separated pieces, it is possible to integrate them into one component by adding some support structures to connect them.

Conclusion: In this Letter, we have reported novel rectangular waveguide filter structures with long slots in the middle of the broad side walls. Such filters facilitate the assembly and reduce the difficulty of joining. An X-band filter with 2% FBW has been designed and tested. The measurement results have good agreement with simulations. The proposed filter structure may find useful application in the design of terahertz waveguide filters or polymer based structures which normally operate at low power level and require a good joint.

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