Ka-band gap waveguide coupled-resonator filter for radio link diplexers

Ka-band Gap Waveguide Coupled-Resonator Filter for Radio Link Diplexers

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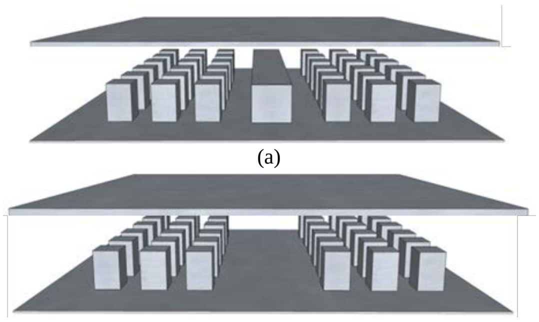
Abstract- **Gap waveguide technology represents an interesting alternative as low-loss, cost-effective and high-performance transmission line and package of microwave and millimeter-wave systems. A Ka-band coupled-resonator filter for a radio link diplexer, which requires high selectivity to isolate transmit and receiving channels, is proposed and realized using gap waveguide technology. The band-pass filter, which has a central frequency of 37.37 GHz and a pass bandwidth of 560 MHz, is fabricated between two metal parallel plates leaving an air gap between them. Measurements show a minimum in-band insertion loss of 1 dB and agree quite well with simulations.**

I. INTRODUCTION

Gap waveguides were first introduced in [1] as a novel transmission line technology. This guiding technology is especially interesting to realize circuits and components at frequencies over 30 GHz up to THz. At those frequencies, the current technologies show some deficiencies regarding to the performance or to the manufacturing complexity. Hollow waveguides are resorted for low-loss applications, but the main handicaps lay in the integration with active components and in the manufacture difficulty that involves a high-cost product. Planar technologies, such as microstrip and coplanar, are suitable for integration and easier to fabricate, but they suffer from higher losses with increasing frequency as well as from the presence of cavity resonances when encapsulated, what entails disruption from the expected performance. Therefore, it is evident the need of new transmission line technologies at the mm- and sub mm-wave bands and beyond. An example is the Substrate Integrated Waveguide (SIW) technology, a more recent proposal that has been widely used in the last years for high-frequency applications [2], but still, it exhibits significant losses at increasing frequencies due to wave propagation in substrate. On the other hand, gap waveguides can be made of only metal so that waves propagate in the air gap between two metal plates. Such waveguides have been presented as interesting candidates to become alternative guiding technology for these frequency bands [1].

Gap waveguides are made between two parallel metal plates. One of the plates is made of a texture, in the form of a bed of nails, to create a high impedance condition at the surface (ideally, a Perfect Magnetic Conducting (PMC) surface), which in turn forces a cut-off for the parallel-plate modes, i.e., wave propagation is forbidden between these two plates as long as the distance between them is less than $\lambda/4$. For the purpose of providing a path to the waves, metal ridges are present in between the nails, in such a way that the waves follow metal ridges confined to the air gap between the ridges and the metal plate on top (see Fig. 1). This is the so-called Ridge Gap Waveguide [1], [3]. In addition, this propagation path can also be provided by a microstrip line lying on the bed of nails, or by a groove in between the nails, giving rise to the Microstrip Gap Waveguide, and the Groove Gap Waveguide, respectively [4].

Waves propagate in the form of a TEM-mode following ridges/strips within the Ridge and Microstrip Gap Waveguides. For the Groove Gap Waveguide, however, propagation is of TE–type. In [5], it was shown that among these three configurations, Microstrip, Ridge and Groove Gap Waveguides, groove gap waveguide resonators provide the highest quality factor (Q). Therefore, resonators in groove gap waveguide have been used in the present paper to realize a Ka-band coupled-resonator filter for a radio link diplexer where the insertion loss requirement is a critical factor.



(a)

(b)

Fig. 1. Sketch of two configurations of gap waveguides: (a) Ridge Gap Waveguide, and (b) Groove Gap Waveguide.

Microwave and RF filters are essential components for most communication systems [6]. Particularly in cellular radio systems, filters are used in microwave links at 38 GHz for communicating between base stations. The base station transmits and receives simultaneously (see Fig. 2). Hence, the diplexer is a critical component of the RF frontend, since it separates the TX and RX signals and at the same time connects them to a common antenna port. These diplex filters require very low insertion loss in the pass band, and high selectivity to reject signal frequencies close to the pass band. In order to fulfill such stringent requirements, these high frequency filters are normally constructed using waveguides. Traditionally, they have been designed with iris filters in rectangular waveguides, but they represent a significant product cost. Moreover, these filters contribute to increase the size and complexity of the system, as these modules in rectangular waveguide must be connected to the electronic modules, which contain active components (MMICs) mounted on a PCB and interconnected through microstrip or coplanar lines. The RF front ends for point-to-point microwave links could benefit from the gap waveguide technology to integrate active and passive parts in the same module. On one hand, gap waveguides can be used to package microstrip circuits without creating cavity resonances, as shown in [7], [8]. On the other hand, they can be used as transmission lines to realize passive components like filters and couplers [9], [10]. In this way, by making use of these two functionalities, gap waveguides can provide complete integration of all parts of the system. Passive and active circuits can be integrated in the same module; even the antenna can be included. Therefore, one of the main advantages of gap waveguide technology is to provide system integration between two parallel-metal plates, which do not require any conducting contact between them. As a result, the system becomes more compact and the manufacturing difficulty and cost are reduced notably. It is worth to mention that for radio links at higher frequencies, like E-band radio, new technologies are needed. It is especially here, for millimeter- and sub-millimeter-wave applications, where gap waveguides represent a promising solution. The demonstration of a complete RF front end for microwave links made in gap waveguide technology is beyond the scope of this paper. Still, it is worth to note that the potential and advantages of gap waveguide technology are more outstanding when applied to a complete system than when used for a single component.

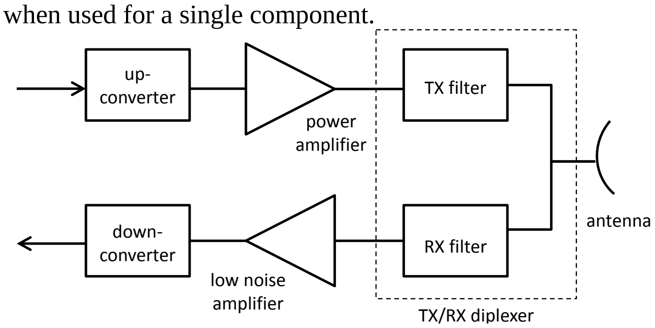


Fig. 2. Block diagram of the RF front end of a cellular radio base station.

The purpose of this paper is to demonstrate whether gap waveguide technology can be used for these narrow-band band-pass diplex filters for radio links at 38 GHz. The stringent specifications of these filters regarding to the low loss and high roll-off require around eight resonators with unloaded *Q* of at least 5000 [6]. So far, to the author's knowledge, only filters made in waveguide can provide such high values of *Q*. Since groove gap waveguide resonators have been shown to provide values of *Q* comparable to those provided by rectangular waveguides [5], it should be possible to design a 38 GHz radio link filter in groove gap waveguide technology. Filter specifications are shown in Section II. Section III describes the design process of coupled-resonator filters. The relationship between filter parameters and filter geometry is established in Section IV, through design curves. Finally, Section V shows simulated and measured results.

II. Filter Specifications

The specifications for the diplex filter shown in Table I correspond to a fractional bandwidth (BW) of 1.5% and involve a steep roll-off to reject signal frequencies within the stop band. The selectivity of a filter increases with the number of resonant sections, but the insertion loss is also increased. Furthermore, the insertion loss is inversely proportional to the filter bandwidth and the resonator *Q*.

TABLE I
Specifications for the 38 GHz Diplex Filter

Pass band	37.058 – 37.618 GHz
Stop band	38.318 – 38.878 GHz
Insertion loss	1.5 dB
Attenuation	70 dB
Return loss	17 dB

III. Filter Design

A general technique for designing coupled resonator filters is used. It can be applied to any kind of resonator despite its physical structure. This technique is based on coupling coefficient of intercoupled resonators and the external quality factors of the input and output resonators. These parameters can be obtained numerically from the frequency response of resonators using an EM solver [11].

Any narrow-band, lumped-element, or distributed band-pass filter can be described by three fundamental variables: the synchronous tuning frequency of each resonator, f_0; the coupling between adjacent resonators, K; and the singly loaded or external Q of the first and last resonators, Q_{ex} [12]. The general band-pass filter design procedure utilizes the normalized, low-pass elements of the prototype filter to determine the required coupling coefficient between resonators and the coupling to the external circuit; that is, the source and load. The low-pass prototype filter is a lumped element network that is synthesized to provide a desired filter transfer function. In this case, a Chebyshev response with 1.8% fractional bandwidth, 70 dB attenuation in the stop band, and 0.01 dB maximum ripples in the pass band, was considered. The graphs and equations in [13] were used to obtain an estimation of the filter order N, and the corresponding normalized low-pass prototype element values for an Nth order filter (N=7 for this case). From the low-pass parameters g_i, the required coupling coefficients (K) and external quality factors (Q_{ex}) are calculated as [12]:

$$K_{i,i+1} = \frac{\mathrm{BW}}{\sqrt{g_i g_{i+1}}}, \quad i = 1, \ldots, N-1 \tag{2}$$

$$Q_{ex_i} = \frac{g_i g_{i+1}}{\mathrm{BW}}, \quad i = 0, N \tag{3}$$

IV. Design Curves

Once the band-pass filter parameters are known, the next step is to establish the relationship between these parameters and the filter geometry. For this purpose, design curves relating the filter parameters (K and Q_{ex}) to certain parameters describing the filter geometry were calculated.

Two resonant peaks are observable from the frequency response of a pair of coupled resonators (see Fig. 3). Once the natural resonant frequencies (f_{high}, f_{low}) of these two peaks are found, the coupling coefficient of two synchronously coupled resonators is calculated as

$$K = \frac{f_{high}^2 - f_{low}^2}{f_{high}^2 + f_{low}^2} \tag{5}$$

For measurement purposes, the input and output resonators are connected to standard Ka-band WR-28 rectangular waveguide flanges. The external quality factor can be obtained from the frequency response of a doubly-loaded resonator as

$$Q_{ex} = \frac{2 \cdot f_0}{BW_{-3dB}} \tag{6}$$

where BW-3dB is the bandwidth at -3dB.

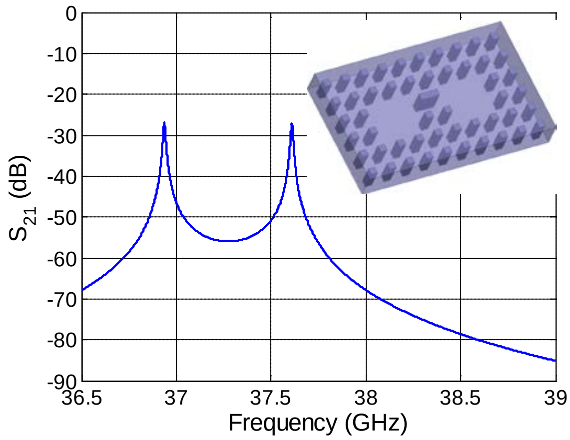


Fig. 3. Frequency response of a pair of coupled resonators.

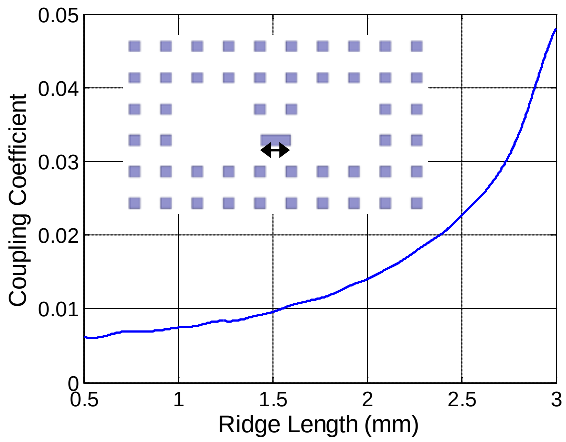


Fig. 4. Coupling coefficient between two coupled resonators as a function of the ridge length.

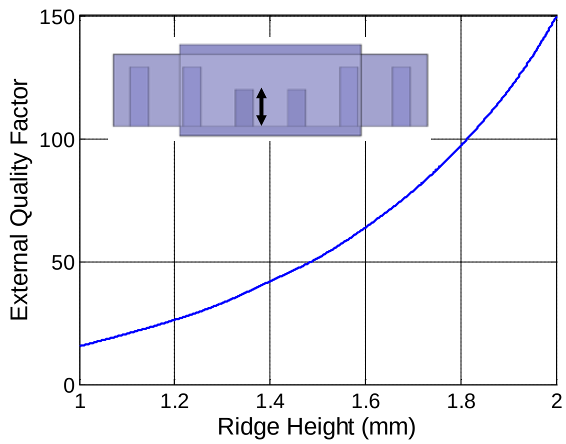


Fig. 5. External quality factor of one resonator doubly-loaded by standard Ka-band WR-28 rectangular waveguide as a function of ridge height. Two ridges as coupling elements between the resonator and the external circuit.

Groove gap waveguide cavities are open structures; however they work in the same way as completely closed resonators. They are created in the region formed by the groove in between the nails on the bottom plate and the flat metal plate on top. Fields are confined to the groove region without the need of any conducting contact between the two metal plates. The bed of nails imposes a cut-off for the parallel-plate modes in the air gap between the two plates, so that fields cannot expand through this gap, and therefore they remain confined to the cavity or groove region. Attenuation is around 20 dB per row of nails, thus, waves are completely attenuated after two rows of nails, more than 40 dB. Dimensions of the bed of nails and air gap height are chosen to show a stop band for the parallel-plate modes between 25 and 50 GHz. Cavity size is selected to provide a resonant frequency of 37.37 GHz.

First, for the study of K between adjacent resonators, two resonators are placed side by side in such a way that adjacent cavities are separated by two rows of nails. A low coupling level is obtained using (5). In order to increase the coupling two nails are replaced by a ridge of the same width as the nails' thickness, as shown in Fig. 3. This coupling can be varied by changing the ridge length, as can be seen in Fig. 4.

Then, the input and output resonators must be loaded, i.e., coupled to the external network, in a proper way, so that the Q_{ext} design value is provided. For measurement purposes, WR-28 rectangular waveguides are connected to the input and output resonators. Two ridges are now used as coupling elements from input/output resonators to the external network. It is assumed that the two ridges are identical, and their width is equal to the nails' thickness. By varying the ridge height it is possible to adjust the external quality factor to the design value, as shown in Fig. 5.

The design curves given by Fig. 4 and Fig. 5 are used to determine the sizes of the ridges which make up the filter.

V. Results

From the previous design process the filter geometry is determined. As expected for a high order filter, the initial filter design does not fulfill specifications and an optimization stage has to be carried out. Cavity sizes and ridge lengths are the parameters considered for the optimization. Cavity sizes are used to tune the resonant frequency of each resonator, and couplings are controlled by means of ridge lengths. Since a symmetric design is assumed, seven parameters in total are taken into account in the optimization. In order to keep a uniform grid of pins, which is very convenient for manufacturing, cavity sizes are increased by sawing the pins at the cavity border. Only a few microns are enough, so in practice the pin size variation is hardly noticeable. A sketch of the filter obtained after optimization and its frequency response calculated in HFSS are shown in Fig. 6 and Fig. 7, respectively. Silver as conducting metal is considered in simulations. As can be seen in Fig. 7, specifications are satisfied. In-band return loss higher than 17 dB and in-band insertion loss less than 1.5 dB are shown. Out-band rejection higher than 70 dB is satisfied as well. The minimum in-band return loss is below 1 dB.

A prototype of the designed filter was manufactured in aluminum and silver-plated afterwards. The filter is made between two metal plates. One of the plates was milled to create the pins and ridges; whereas the other plate was placed above it keeping a certain distance between them, i.e., an air gap. Thus, this filter has no sidewalls (see Fig. 8). Such a property can be an advantage with respect other cavity-based filters, as it allows airing and cooling, and in consequence it can be less sensitive to temperature drift. The fact of not requiring conducting contact between plates is also an advantage, already at this frequency, but especially at higher frequencies where the leakage through joints becomes more marked. Fig. 7 shows the comparison between simulations and measurements. The measured pass band is moved approximately 75 MHz to lower frequencies with respect to simulated one. This difference is due to manufacturing tolerances, since the milling technique used has an accuracy of ±30 μm. Regarding to the minimum in-band insertion loss, simulated and measured results differ only 0.1 dB. But measurements show that return loss is not better than 17 dB within the whole pass-band due to degradation of one of the poles. Still, the results are acceptable. Nevertheless, it is also possible to tune the pass band by means of tuning screws inserted in the cavities through the top metal plate.

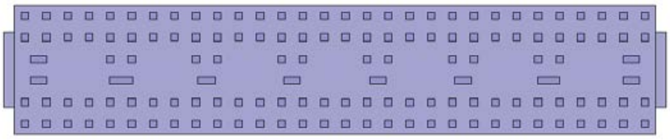


Fig. 6. Sketch of the optimized coupled-resonator filter in groove gap waveguide technology.

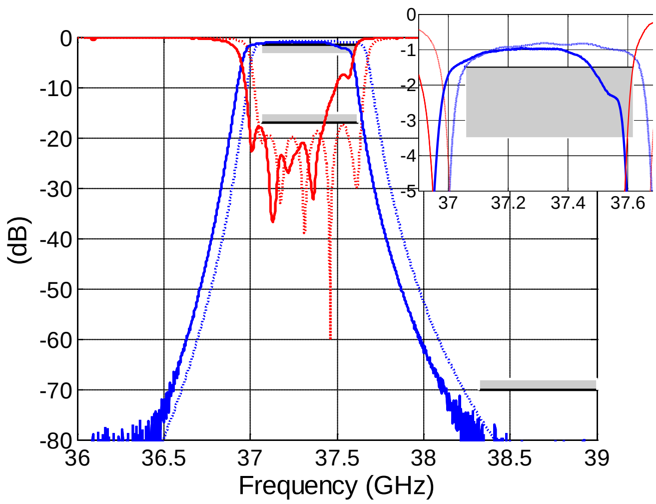
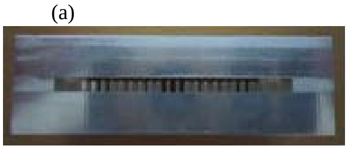


Fig. 7. Filter responses: measured (solid line) and simulated (dotted line). Specifications are also shown for reference (black lines).

(a)

(b)



(c)

Fig. 8. Photos of the filter prototype: (a) Top and bottom plates (with holes to assemble both parts), (b) Front view (with holes to connect rectangular waveguide flanges), (c) Side view (with no sidewalls).

VI. Conclusions

A narrow-band filter for a 38 GHz radio link diplexer has been demonstrated in a recently introduced technology, the gap waveguide. A coupled-resonator filter has been designed by using groove gap waveguide resonators. Their high Q, comparable to the Q of rectangular waveguide resonators, makes stringent specifications fulfillment possible. Low insertion loss and high selectivity are required for these narrow-band filters. They are very sensitive to manufacturing tolerances, but still, measurements agree quite well with simulations.

Acknowledgment

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