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A Novel Tap Input Coupling Structure for a Narrow Bandpass Filter Using TM_{010} Mode of a Microstrip Circular-Disk Resonator

Kenneth S. K. Yeo and Michael J. Lancaster

***Abstract*—This paper discusses a new method to couple into the TM_{010} mode of a microstrip circular-disk resonator. This method can achieve reasonably strong input coupling, which is useful for narrow-band filters with fractional bandwidths of approximately 0.5% and above. A comparison between this newly proposed input coupling structure and the conventional gap input coupling structure will be addressed. A decision threshold for using either the tap input or the conventional gap-coupled input is also explained. Experimental results of a filter fabricated using this novel input coupling structure is also presented.**

***Index Terms*—Disk resonator, filter, HTS.**

I. Introduction

The TM_{010} mode of a microstrip circular-disk resonator is a very promising structure for high-power high-temperature superconductor bandpass filters because of its edge-free current distribution [1]. This paper presents a new input coupling structure for the TM_{010} mode of microstrip disk resonator, which can achieve the required input coupling for narrow-band filter design. This input coupling is controlled by tapping between the open- and short-circuit points along the radius of the microstrip circular disk.

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Conventionally, input gap coupling is used to couple into the disk resonator [2]. The disk filter in [2] employs the TM_{110} mode instead of the TM_{010} mode, which is discussed here. Since the charge density of the TM_{110} mode of circular disk is maximum at the edge [3], reasonably strong coupling can be achieved using the gap-coupled input. However, gap coupling for the TM_{010} mode is very weak because charge density is not maximum at the edge. Therefore, it can only be used to design very narrow-band filters, i.e., smaller than 0.5% of fractional bandwidth (FBW).

Another method to couple into the TM_{010} mode of circular disk is to use a coupling pin, which is inserted onto the top of the disk (without touching) [4]. This method provides similar coupling strength compared to the gap-coupled input because the coupling mechanism is through the charge density (or electric field). This method has its advantages over the gap-coupled input because no perturbation of the disk is introduced. However, the pin-coupled input is difficult to control because positioning of the pin is subject to mechanical machining tolerance. Furthermore, the external Q factor using this method is also difficult to determine using planar electromagnetic (EM) simulators. It should be pointed out here that the input coupling and the external Q factor are inversely proportional [5] and both terms are used extensively in this paper.

The newly proposed method in this paper also has a disadvantage, which is the slight perturbation of the disk, but it can provide reasonably strong input coupling. Furthermore, the external Q factor can be easily determined using a planar EM simulator. Due to this factor, this method is useful for practical filter design.

II. Input Coupling

A microstrip disk resonator is a circular conducting disk patterned onto a dielectric substrate with a ground plane on the opposite side. The tap input coupling can be easily achieved by making a via through the dielectric substrate and ground plane to the patterned disk resonator. However, for a high-temperature superconductor thin film, which grows on a single crystal substrate, i.e., magnesium oxide (MgO), lanthanum–aluminate ($LaAlO_3$), or sapphire, making a via through the ground plane cannot be easily achieved. For this case, the tap input can only be achieved by making a notch into the disk resonator and inserting the 50-Ω feed line into the disk, as shown in Fig. 1(a).

The external Q factors of the input feed can be varied by changing the tap location T along the radius of the disk. The current distribution flows radially with the minimum at the center and the edge of the disk and the peak at about one-half the radius. A plot of the normalized current distribution is shown in Fig. 2. This plot is based upon the theoretical model for the field equations [6] of the microstrip circular-disk resonator. The X- and Y-axes are normalized to the radius R of the disk.

The external Q factor of the new tap input structure is simulated using ***em*** Sonnet [7]. To make comparison between the new tap input and the conventional gap coupled, a similar structure is also simulated, as shown in Fig. 1(b). The simulation results are shown in Fig. 3. The insertion point t is normalized to the radius of the disk, i.e.,

$$t = \frac{T}{R} \tag{1}$$

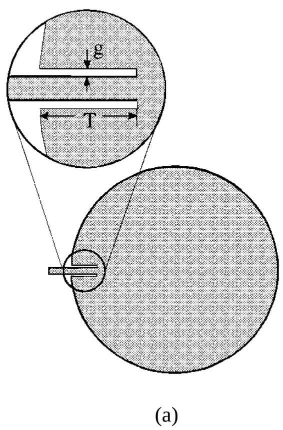

Fig. 1. (a) Tap-coupled input and (b) gap-coupled input of a microstrip circular-disk resonator.

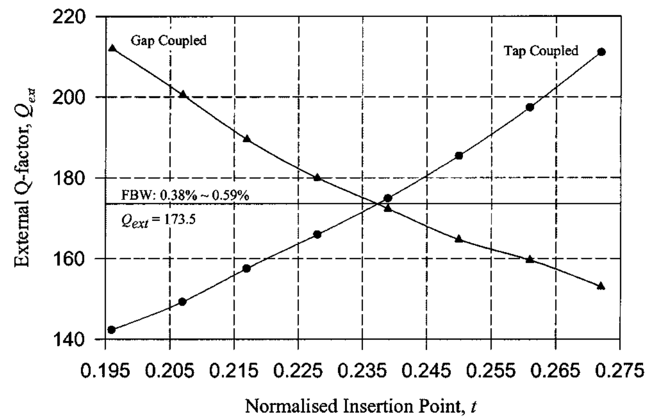

Fig. 3. Simulated results of the external Q factor for the tap-coupled and gap-coupled inputs of the TM_{010} mode of a circular disk.

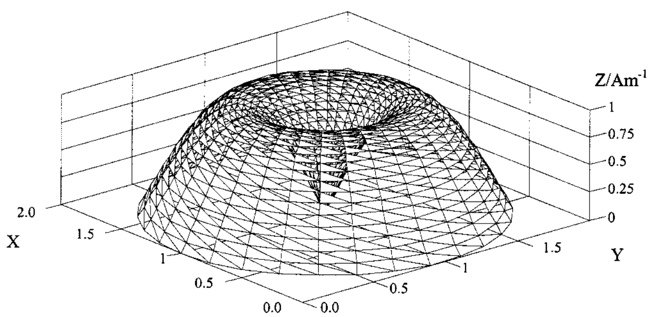

Fig. 2. Normalized current distribution of the TM_{010} mode of a circular-disk resonator. X- and Y-axes are normalized position on the circular disk and the Z-axis (vertical axis) is the normalized magnitude of the surface current.

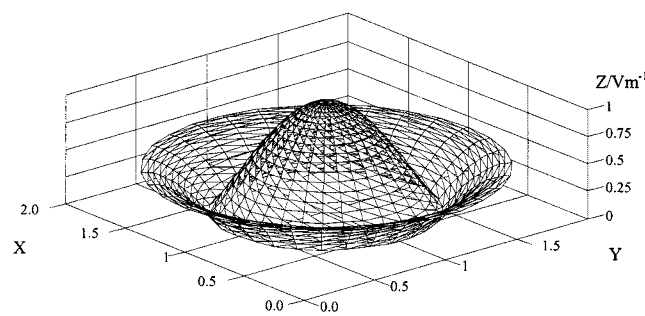

Fig. 4. Normalize charge density distribution of the TM_{010} mode of a circular-disk resonator. X- and Y-axes are normalized position on the circular disk and the Z-axis (vertical axis) is the normalized magnitude of the charge density.

where T is shown in Fig. 1 and R is the radius of the disk. By normalizing T to the radius, the tap-coupled input has some similarity to a tap input (or shunt) to a 50-Ω half-wavelength resonator [8], [9] where its short-circuit point is at $t_{50\Omega} = 0.5$ and the open-circuit points are at $t_{50\Omega} = 0$ and 1 ($t_{50\Omega}$ is normalized to a half-wavelength or π). However, it must be pointed out that the current distribution of the disk is not perfectly symmetrical about $t = 0.5$. The gap g in Fig. 1 is fixed at 100 μm. One may argue that reducing g will increase the input gap coupling, but reducing g will also complicate the fabrication process, as pointed out in [2].

From Fig. 3, it is shown that the external Q factor for the tap and the gap-coupled inputs crossover at $t = 0.237$, which corresponds to the external Q factor of 173.5. This external Q factor value corresponds to a Chebyshev bandpass filter with FBW in the range of 0.38%-0.59% [10]. The lower and upper limits of FBW are computed based on two- and ten-pole Chebyshev functions, respectively, with 20-dB return loss. A range is quoted here instead of a specific value because the external Q factor is not just dependant on the FBW, but also on the passband ripples and number of poles. For narrow-band filters that have FBW smaller than this range, the gap-coupled input posed a better option because the required external Q factor can be achieved with less perturbation compared to the proposed method. However, for filters that require an external Q factor smaller than 173.5, the proposed method is a better option. Therefore, the external Q factor of 173.5 can be used as a decision-making tool for which input coupled structure to use when designing a TM_{010}-mode circular-disk filter. Due to these two input coupled structures, a wide range of narrow-band filters can be achieved without inserting the feed line more than $t = 0.237$.

If the insertion point continues to be increased, the external Q factor of the tap-coupled input will form an asymptote at $t \approx 0.5$ (exact value is 0.52). The gradient of the curve also increases dramatically when t approaches 0.52. Therefore, the external Q factor is very difficult to control as t is close to the asymptote because the coupling is very sensitive to the tap location, i.e., making small changes to the tap location will lead to large changes in the external Q factor.

Since the current is flowing radially from zero at the center to zero at the edge and peak at $t \approx 0.5$ of the disk, it is very easy to assume that the charge density is maximum at the edge and the center of the disk. However, this is not the case, as shown in Fig. 4. The charge density at the edge is less than one-half compared to the center of the disk. This is one reason why the gap-coupled input is so weak at the edge of the disk. The relationship between the external Q factor and the charge density distribution is not obvious. One would expect the external Q factor to increase with the decrease of the charge density. The charge density is reduced when moving away from the edge of the disk. However, inserting the feed line into the disk, the overlap fringing field from the feed line to the disk is increased. Therefore, the input coupling is increased instead of reduced. The external Q factor levels off when t approaches 0.372, which is the zero charge density point. Increasing t further will decrease the external Q factor further.

Strong input coupling (or lower external Q factor) can be achieved using a tap-coupled input, and weak input coupling can be achieved using a gap-coupled input. Therefore, if both the tap and gap input coupled structures are used hand-in-hand, there is no limit for FBW that can be achieved for this type of filter.

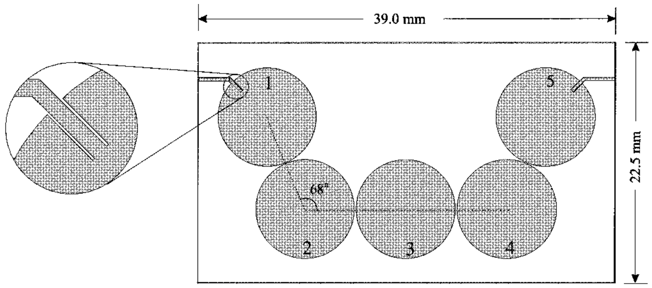

Fig. 5. Layout of a high-temperature superconductor five-pole disk filter using the TM_{010} mode.

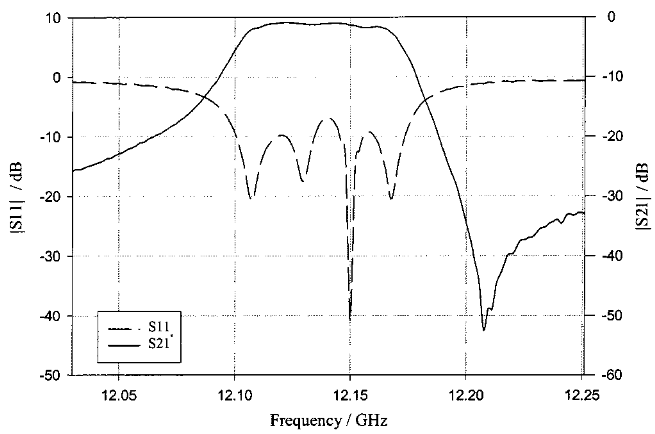

Fig. 6. Experimental results of the five-pole YBCO filter at 60 K.

III. Filter Example

To show the validity of the newly proposed input structure, a five-pole Chebyshev filter was fabricated and tested [11]. The FBW of this filter is approximately 0.5%. The inter-resonator couplings can be determined using ***em*** Sonnet [6]. By simulation of two circular-disk resonators, two resonant peaks can be observed. The coupling coefficients between the disks can then be computed based on [12].

The layout of the filter is shown in Fig. 5. The filter was fabricated using yttrium–barium–copper–oxide (YBCO) microstrip on sapphire substrate with thickness of 0.33 mm and dielectric constant of 9.6. The filter was cooled down to 60 K using a closed-cycle cryostat and the measurement was made using an HP8720A network analyzer. The measured results are shown in Fig. 6. The midband insertion loss is measured at 0.8 dB at 12.14 GHz. The insertion loss may seem low compared to other high-temperature superconductor filters, which operated at lower frequency, and have been published in the literature. The high insertion loss can be attributed to the dramatic increase of the surface resistance as frequency increases since high-temperature superconductor thin-film surface resistance is direct proportional to the frequency square. A transmission zero is observed at the high-frequency region. This observation occurs due to coupling between input and output (i.e., coupled through between input and output). As a result, a higher selectivity at the upper sideband occurs at the expense of the lower sideband.

IV. Conclusion

We have introduced a new input coupling structure for the TM_{010} mode of a circular-disk resonator. The tap-coupled input discussed in this paper is only applicable to the TM_{010} mode of circular-disk resonators because of their unique current distribution. This tap-coupled input does not hold for other modes in the circular disk.

The tap-coupled input can provide stronger input coupling compared to the gap- or pin-coupled input. Therefore, the tap input coupled will widen the FBW range in the design of a narrow-band filter. We have also shown the decision point (with respect to the external Q factor) in determining the best input structure for designing the TM_{010} mode of a circular-disk narrow-band filter. By making this decision, the perturbation of the disk resonator can be minimized.

We have also provided a plot of the normalized charge density for the TM_{010} mode of circular disks. This plot is not normally found in the literature because most researchers are only interested in the current distribution of this mode. Experimental results of an high-temperature superconductor five-pole filter is also shown in support of the new tap input structure.

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