HTS Quasi-Elliptic Filter Using Capacitive-Loaded Cross-Shape Resonators With Low Sensitivity to Substrate Thickness

Alonso Corona-Chavez, *Member, IEEE*, Michael J. Lancaster, *Senior Member, IEEE*, and Hieng Tiong Su, *Member, IEEE*

***Abstract*—The design and implementation of a four-pole quasi-elliptic filter for X-band radar applications using high-temperature superconductors is presented. The resonators used consist of cross-shape ring resonators with additional interdigital capacitive loads that allow miniaturization with reduction of sensitivity to substrate thickness. The experimental and simulated results are shown together with the power dependence of the filter.**

***Index Terms*—Bandpass filter, high-temperature superconductor (HTS), intermodulation distortion (IMD), quasi-elliptic response, radar systems, superconductor, X-band.**

I. Introduction

FOR X-BAND radar applications, superconducting materials offer the advantages of miniaturization of the circuits by using high-permittivity substrates without deterioration of power loss performance. At 10 GHz, the surface resistance (R_s) of thin film $YBa_2Cu_5O_7$ (YBCO) is in the order of $10^{-5}\ \Omega$ at 77 K, while copper at the same temperature has an R_s of approximately $10^{-2}\ \Omega$ [1]. This low surface resistance in high-temperature superconductors (HTSs) translates into a longer range in radar receivers because the receiver sensitivity increases due to their lower noise figure compared to conventional technologies.

Common radar systems for electronic warfare incorporate delay lines of several nanoseconds, filters, and low-noise amplifiers (LNAs) in their front-ends, all of which can use HTS materials [2]. It is, therefore, practical, by integrating all the components using one cryo-cooler, to produce compact and high-performance systems. Ryan [3] describes several HTS filters for improved warfare systems at X-band. In [4], a delay line is presented having a delay of 35 ns at around 10 GHz with a loss of approximately 1 dB. In [5], an HTS diplexer at X-band using two branch-line couplers and two-pole filters with half-wavelength-long resonators is shown. In [6], a narrow band (0.5%) HTS filter is also shown at X-band and, in [7], a front-end receiver module for a radar at X-band is demonstrated integrating an LNA and an eight-pole 2% bandwidth filter.

For mass production of planar HTS filters, it is desirable to have trimmingless circuits [8]. The main causes of performance variation for the designed filters are manufacturing tolerances and nonuniformity of substrate thickness, the latter being the most significant one [9].

Numerous efforts have been carried out to reduce the sensitivity to tolerances in substrate thickness. In [10] and [11], novel single-mode microstrip resonators, which need little tuning, are shown. One other way of making resonators with little sensitivity to substrate thickness is using coplanar structures; however, for larger circuits, it is necessary to balance the ground planes with extra bond wires, incrementing crosstalk and manufacturing difficulties [12]–[14].

In this paper, the design of a novel quasi-elliptic four-pole filter for X-band radar applications is presented using dual-mode cross-shaped ring resonators with capacitive loading. The advantage of these resonators is that they are considerably smaller than conventional ring resonators [15]–[19] and they present little sensitivity to substrate thickness. In [20], copper versions of such resonators were verified experimentally and filters with Chebyshev responses were demonstrated. However, it is possible to implement quasi-elliptic configurations. The principle behind this type of resonator lies in the fact that an interdigital capacitor in a microstrip structure would concentrate the electric field near the surface, thus making it less sensitive to variations in the thickness of the substrate, as less field would cross down to the ground plane [21].

One of the main drawbacks of HTS technology is their potentially poor power-handling capability caused by their power-dependent nonlinear behavior of surface resistance. This nonlinear behavior generates odd harmonics (third, fifth, seventh, etc.) and two-tone intermodulation in the filters. The power-handling capabilities of the filter will be mentioned later with experimental data.

II. Resonator Characteristics

A ring resonator is a 360° closed-loop transmission line. Two orthogonal modes can be excited if one or several notches are inserted in one or more corners of the resonator [17].

The addition of the interdigital capacitor to the resonator has the effect of concentrating the electric fields near the surface, hence reducing its sensitivity to substrate thickness.

Simulations, assuming a lossless metal on the MgO substrate ($\varepsilon_r = 9.7$ and $h = 0.5$ mm) at a center frequency of 9.4 GHz, were carried out to prove this concept. Using the cross-shape ring resonator, interdigital capacitors were added with different number of fingers (from 2 to 11). All the resonators were weakly

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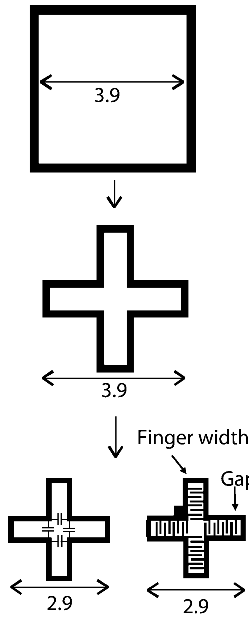

Fig. 1. Size comparison of conventional ring resonator and capacitive loaded cross resonator on MgO ($\varepsilon_r = 9.7$, $h = 0.5$ mm) at 9.4 GHz.

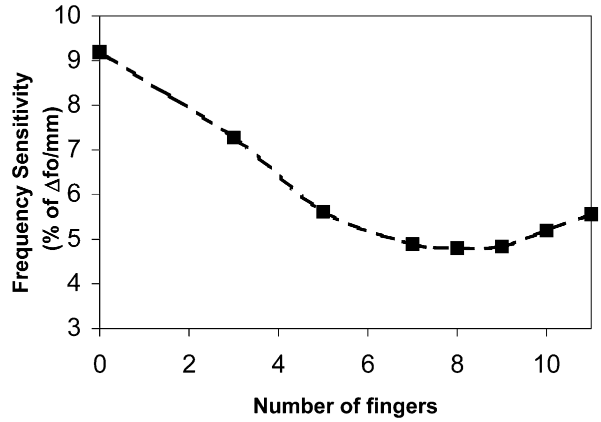

Fig. 2. Sensitivity to substrate thickness of cross-shape resonators with different interdigital fingers. Simulations were carried out assuming MgO substrate ($\varepsilon_r = 9.7$).

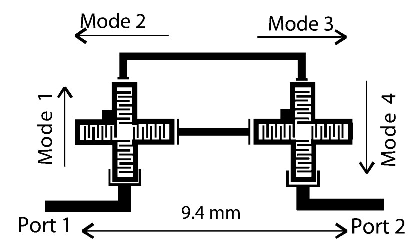

Fig. 3. Final layout of quasi-elliptic four-pole filter at X-band.

coupled to prevent any effect from the feed lines and then were simulated in an electromagnetic simulator [22] at different substrate thicknesses. The structure dimensions are shown in Fig. 1. Fig. 2 shows the sensitivity of the resonator in terms of the deviation of center frequency per millimeter of substrate variation (Δf) versus the number of fingers in the interdigital capacitor. Δf is given by

$$\Delta f = \frac{\Delta f_o}{\Delta h \times f_o} \times 100 \tag{1}$$

where Δf_o is the variation of the resonant frequency, Δh is the difference in substrate thickness, and f_o is defined as

$$f_o = \frac{f_{o1} + f_{o2}}{2} \tag{2}$$

where f_{o1} and f_{o2} are the resonant frequencies of the resonator with different substrate thicknesses. As can be seen in Fig. 2, the sensitivity decreases from approximately $\Delta f = 9.2\%$/mm (with zero fingers) to approximately $\Delta f = 4.7\%$/mm (with eight fingers). However, as the number of fingers increases, the parasitic capacitance to ground does as well. This effect becomes evident in this structure for nine, ten, and 11 fingers when the sensitivity to substrate thickness starts rising (4.8%/mm, 5.2%/mm, and 5.6%/mm, respectively).

By adding the interdigital capacitance, reduction in size is also achieved by capacitive loading. Fig. 1 shows the conventional ring resonator, cross-shape ring resonator [23], and cross resonator with capacitive loading all to scale and operating at the same frequency. As can be seen, the introduction of interdigital fingers also reduces approximately 1.8 times the size of the resonator.

III. Quasi-Elliptic Filter Design

A novel four-pole quasi-elliptic 2%BW filter has been designed using these resonators following the design procedure presented in [24]. The desired coupling coefficients for a maximum return loss of -20 dB and $\Omega_a = 1.8$ are $Q_e = 48$, $k_{12} = 0.017$, $k_{23} = 0.016$, and $k_{14} = -0.0044$, where Ω_a is the frequency variable that determines the position of the transmission zeros, Q_e is the external coupling, and k is the coupling coefficient between different resonant modes.

To obtain the quasi-elliptic response, it is necessary to cross couple nonadjacent resonators or resonant modes. It is important to note that, for clarity, the two resonant modes of the first resonator are called 1 and 2, whereas for the second resonator, they are called 3 and 4, as shown in Fig. 3. For a four-pole Chebyshev filter, resonant mode 1 couples to 2 by the addition of the notch, resonant mode 2 is directly coupled to resonant mode 3, and finally, resonant mode 3 is coupled to 4 by the notch. However, if a quasi-elliptic response is to be achieved, an extra cross coupling between resonant modes 1 and 4 has to be added, as shown in Fig. 3.

IV. Simulation and Experiments

The filter was fabricated on an MgO substrate with permittivity $\varepsilon_r = 9.7$ and thickness $h = 0.5$ mm. The superconductor is YBCO. The circuit is packaged in a metal box with a titanium carrier coated with gold. This assembly was placed in a Grifford–MacMahon closed-cycle cryostat at 30 K.

Fig. 4 shows the simulated lossless response using [22] and the tuned measured one. The center frequency is 9.25 GHz and the bandwidth is 2%. The insertion loss is less than 1 dB throughout the band, and the maximum ripple is 0.25 dB. The return loss of the tuned response is lower than -13 dB throughout the band. The two transmission zeros are placed at

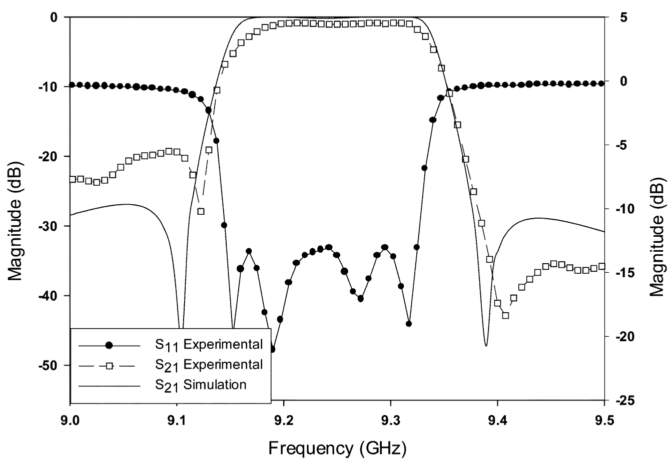

Fig. 4. Experimental and simulated data for four-pole quasi-elliptic filter.

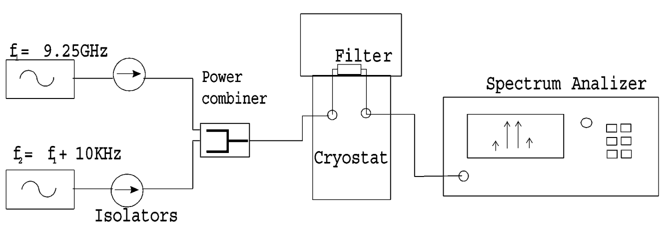

Fig. 5. Experimental setup for IMD measurement.

9.12 and 9.41 GHz. In this figure, the simulated response is overlapped for comparative purposes. There is good agreement between simulated and experimental data. A frequency shift of approximately 1.6% from 9.4 to 9.25 GHz is observed, which is thought to be due to substrate permittivity variation. Moreover, patterning tolerances and nonuniformities in the substrate thickness can cause variances in the different coupling coefficients throughout the structure. This is believed to be the main cause of the asymmetric lower than predicted rejection below the passband and higher rejection above the stopband.

The nonlinear characteristics of the filter were examined by performing an intermodulation distortion (IMD) experiment. The experimental setup is shown in Fig. 5, and it consists of two power sources with frequencies $f_1 = 9.25$ GHz and $f_2 = f_1 + 10$ kHz, which are combined by a power combiner connected to the filter placed inside the cryostat at a temperature $T = 30$ K. The power levels entering the filter (P_{in}) varied from -35 to -15 dBm. The values of the fundamental and third harmonic products were recorded and plotted in Fig. 6. As can be seen, the third-order intercept point (the value at which the magnitude of the third harmonic crosses the fundamental) is approximately 80 dBm. The value of the slope for the third harmonics is approximately $1.9:1$. This is consistent with data from several authors [25]–[28] where the slopes vary from $1.6:1$ to $3:1$. Although the causes that induce this non $3:1$ variation are not yet fully understood, some explanations have been presented [29]–[31].

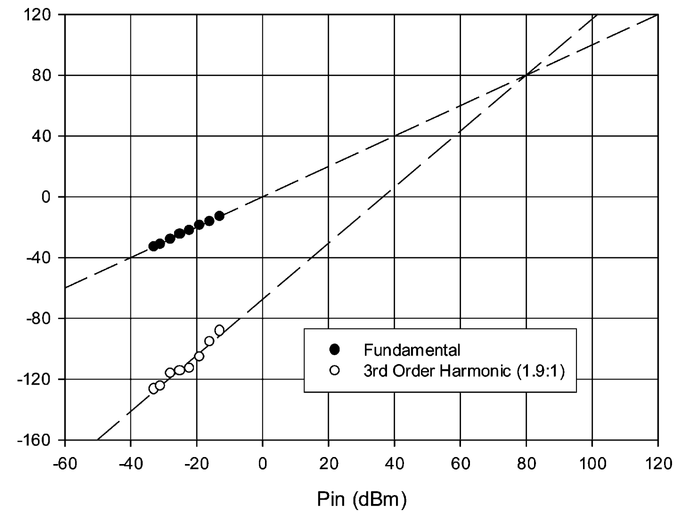

Fig. 6. Input power dependence of third-order IMD power and fundamental modes.

V. Conclusion

A novel superconducting quasi-elliptic filter has been presented using cross-shape resonators with capacitive loading for X-band radar applications. It has been proven that these resonators present lower sensitivity to substrate thickness and they offer size miniaturization. Good agreement was achieved from the electromagnetic simulation and the measured response. The loss was not greater than 1 dB throughout the band and the return loss better than -13 dB. Additionally, an IMD experiment was realized and the shown data coincides with the available literature.

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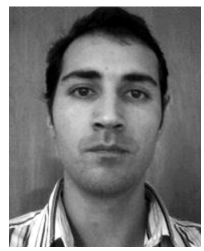

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