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FERRITE-FREE CIRCULATOR FOR PRECISE MEASUREMENTS OF SRF CAVITIES WITH HIGH Q-FACTOR

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Abstract

In this work, we suggest and investigate new magnetless circulators based on three resonators connected in a loop and parametrically modulated in time with mutual phase lag. The first design consists of three Fano resonators with a spectrally asymmetric response, in contrast to schemes based on the Lorentz resonators explored thus far. The second design includes three Fano-Lorentz resonators, i.e., it also possesses spatial asymmetry. We demonstrate that the asymmetric approach provides strong and reversible isolation for the practically feasible modulation amplitude and rate. The results of our work are promising for precise measurements of superconducting radio frequency cavities with high Q-factor.

INTRODUCTION

Superconducting radio frequency (SRF) accelerators at modern scientific nuclear and high-energy physics facilities require continuous-wave operation with accelerating gradients of up to 20 MV/m. To operate in such a regime, SRF cavities must have low cryogenic losses and high intrinsic Q-factor. Recent breakthroughs in SRF technologies, such as nitrogen doping, fast cooling, and coating with novel materials, have improved the quality factor, which is now approaching levels of 10^{11} [1]. These cavities require affordable, reliable, and high-precision instruments to measure such a high Q-factor, especially *in situ*.

Precise Q-factor measurement can be done with an RF power balance technique by measuring the loss of power, which is the difference between input and reflected power. It is now recognized that significant errors can occur when performing these measurements with high intrinsic Q_0 values, especially when not critically coupled. These errors arise from variations in power measurements due to poor directivity, nonlinear losses, and phase/power-dependent effects [2].

A typical diagnostic system consists of four principal elements: RF probe, directional coupler, circulator, and RF load. All these components must have a low voltage standing wave ratio (VSWR) and high directivity in order to calculate the cavity power loss independently from the external Q-factor. Otherwise, systematic errors in cavity power measurement will be introduced [3]. Currently, the accuracy of ferrite-based circulators is limited by the power dependence of the ferrite's material properties, resulting in match and directivity parameter dependence [4]. Reducing the mismatch by eliminating ferrite can improve the accuracy of low-power Q-factor measurements of near-critically coupled cavities in the vertical test. Another important reason for eliminating magnetic materials is the ability to put the circulator into a cryomodule for in-situ measurements of the Q-factor during the cavity operation.

MAGNETLESS CIRCULATOR

A circulator is a three-port nonreciprocal device. Reciprocity implies that the wave transmission between any two points in an arbitrary system is the same for opposite propagation directions as far as the time-reversal symmetry is preserved [5]. As mentioned above, conventional circulators utilize the approach to time-reversal symmetry breaking and nonreciprocity based on magnetic field biasing, which suffers from bulkiness and loss, motivating researchers and engineers to search for more practical approaches. Several approaches to magnetless isolation and circulation have been suggested, including new materials, parametric time modulation, active structures, nonlinearity, unidirectional gain and loss, etc. [6].

The concept of constructing an isolator using Lorentzian and Fano resonators, inside which there is such a nonlinear element as a varactor, is described in [7]. However, the practical realization of a 3-port circulator for cavity measurements based on this nonlinear approach is challenging because of the presence of reflected signals in all ports, which can destroy the asymmetry and hence nonreciprocity. To get around this obstacle, one can utilize an approach based on the time variation of resonant frequencies of three resonators connected to form a 3-port system. In contrast to the nonlinearity approach, the time variation approach to nonreciprocity does not suffer from the backscattered fields and hence allows the realization of a circulator.

Recently, Estep et al. [8] introduced the concept of what is currently known as STM-AM (spatiotemporal modulation – amplitude modulation) biasing to realize magnetless circulators. A conceptual diagram illustrating this concept is shown in Fig. 1. Here three resonators are coupled to form a resonant loop and their natural oscillation frequencies are modulated with signals having 0°, 120°, and 240° phases.

In our work, we used the advantages of both nonlinear and time modulation approaches to building a circulator. Two cases were considered: one using modulation time-modulated Lorentzian-Fano resonators similar to those described in work [7] and the simplified version comprising only Fano resonators. Both approaches demonstrate strong isolation (>30dB), but the latter one is simpler and less dependent on the input signal power.

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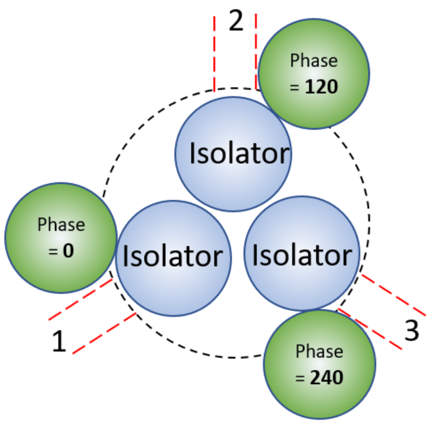

Figure 1: Modulation scheme with 120-degree phase difference between modulation sources.

TWO PORT ISOLATOR

First, we designed a nonlinear 2-port element yielding nonreciprocal port-to-port transmission under continuous-wave excitation. This isolator is based on coupled symmetric Lorentzian and asymmetric Fano resonances, similar to [7]. The RF design of this nonreciprocal Fano-Lorentzian-based isolator was performed in CST Microwave Studio and demonstrated in Fig. 2 and isolation is shown in Fig. 3. A series of simulations were conducted to optimize the scheme for isolation level > 35 dB and simplicity.

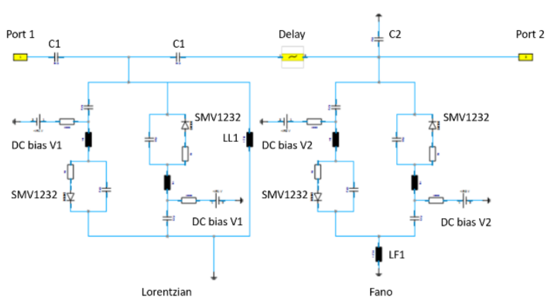

Figure 2: The RF design of this nonreciprocal Fano-Lorentzian-based isolator.

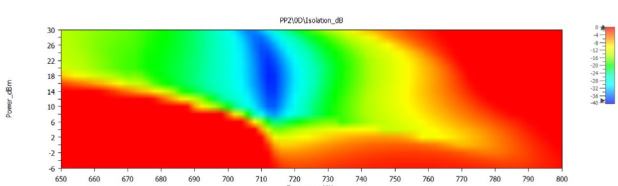

Figure 3: Simulating results for the isolator with two Lorentz and two Fano resonances. The isolation level is 38 dB.

We have then built a test prototype for experimental demonstration of nonreciprocity and isolation (Fig. 4). The prototype consisted of two PCBs (one for each resonator), while the second one had only one integrated PCB. Nonreciprocity was demonstrated by measuring the frequency response of this module when the signal was excited from either end. The prototype demonstrated 6.3 dB isolation with -13 dB direct transmission (Fig. 5).

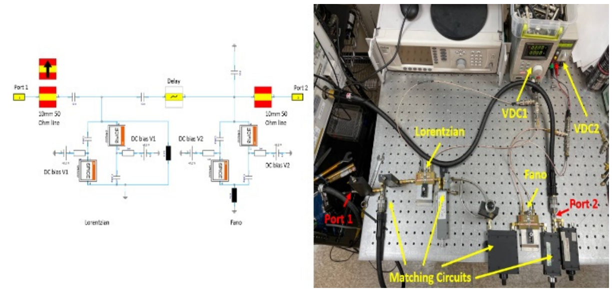

Figure 4: Schematics (left) and the experimental prototype of a nonreciprocal isolator (right), based on coupled Fano-Lorentzian resonators with a nonlinear capacitive element (varactor).

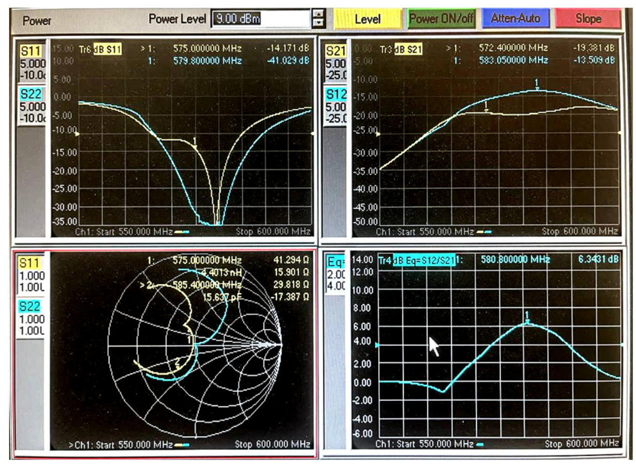

Figure 5: Measured reflection (S11, S22) (left) and transmission (S21, S12) parameters, showing isolation (=of 6.3 dB (right) in the 2-port isolator prototype.

THREE PORT CIRCULATOR

In the next step, we investigated the circulator based on three isolators connected in a triangle circuit. Each varactor has a voltage bias modulated in time. The modulation of each isolator has a phase shift of 120 degrees. We have studied two approaches: the first one is based on three Fano-Lorentz resonators with a spectrally asymmetric response (Fig. 6, left) and only Fano-resonator-based isolators (Fig. 6, right).

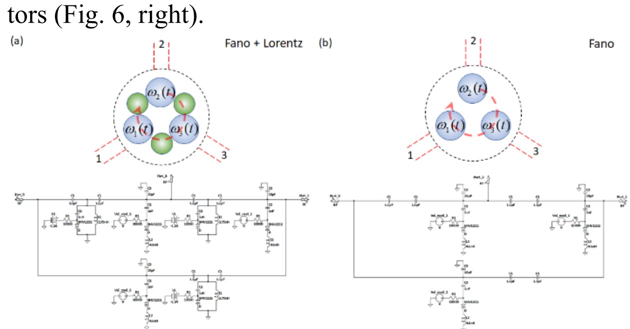

Figure 6: 3-port circulators based on three resonators connected in a loop and parametrically modulated in time with a phase shift. Left: with Fano-Lorentz resonators. Right: The first with only Fano resonators.

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The level of isolation in this circuit depends on the amplitude of the modulation signals and on the frequency of the modulation signals (Fig. 7). We have found the modulation amplitude at a varactor of 0.3V and frequency of 30 MHz, leading to the maximum isolation level of 32 dB (Fig. 8).

At the same time, by applying this bias, the resonator changes its frequency by almost 50 MHz, as shown in Fig. 9. Due to the fact that the phase in each arm of the circulator has a different value, the capacitances of the diodes in the varactors will also have different values, leading to a shift in the resonant frequency of the Fano resonators. Therefore, the symmetry of the circulator's arms vanishes, leading to the introduction of nonreciprocity and isolation.

The achieved isolation value is close to the characteristics of state-of-the-art nonlinear isolators. However, the other parameters, such as reflections and insertion losses, must be further improved by adding matching the ports and reducing the internal losses.

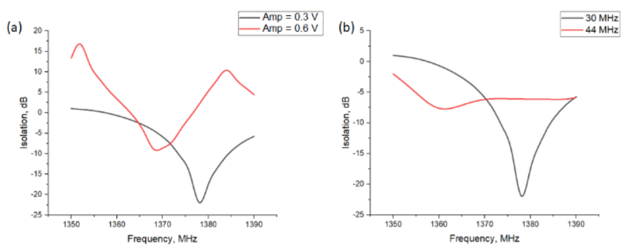

Figure 7: Isolation (dB) of the Fano-Lorentz circulator for various modulation amplitudes (a) and modulation frequency (b).

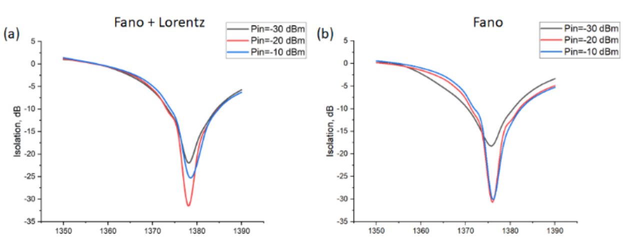

Figure 8: Isolation (dB) of the (a) Fano-Lorentz circulator [see Fig. 6(a)] and (b) the Fano [see Fig. 6(b)] circulator for three different values of the power of input power.

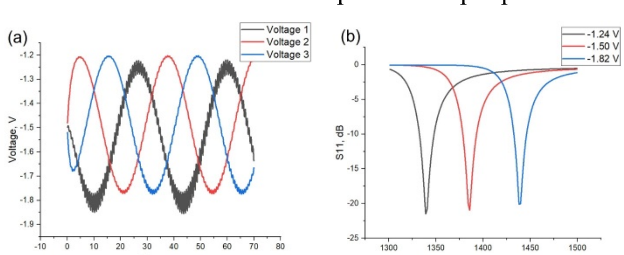

Figure 9: AC voltage bias at phase differences of 120° per ventil (left). Dependence of the Fano resonance on the applied DC voltage bias amplitude (right).

CONCLUSION

We performed an in-depth survey of different approaches toward ferrite-free nonreciprocity and considered several options [5]. As a result of these studies, we decided to focus on the combination of two promising approaches: nonreciprocity realized by nonlinearity combined with asymmetry and time modulation.

To this moment, we experimentally demonstrated isolation in the 2-port device. We designed a 3-port circulator based on time modulation and demonstrated its proof-of-principle via simulations. Both Fano/Lorentzian and Fano approaches demonstrate strong isolation >30 dB, but the circulator's design based solely on the Fano resonator is simpler and more stable to the power of the input signal.

We are currently working on a 3-port circulator proof-of-principle prototype to demonstrate the isolation effect experimentally. The proposed device can also be used in many other applications, including full-duplex systems and protecting superconductor quantum computers' fragile states from thermal noise.

ACKNOWLEDGMENT

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