

A Compact and High-Power Frequency-Selective Plasma Limiter with an Ultra-High Isolation

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Abstract— A novel frequency-selective limiter is introduced in this paper, which is based on integrating a plasma cell into an absorptive resonant topology. The limiter response transitions from all-pass to bandstop when the input power exceeds the threshold for gas breakdown inside the plasma cell. This is a consequence of the change from constructive interference in the all-pass mode to destructive interference in the bandstop mode due to the change in dielectric properties of the plasma cell. Implemented using two quarter-wave microstrip resonators, a gas discharge tube (GDT) as a plasma cell, and a delay line, a less than 1.6 dB loss, over 60 dB selective isolation with a measured FBW of 2.8% were achieved. This is despite the low-quality-factor resonators used in this prototype device and the intrinsic plasma loss. The limiter handles significantly high input power of over 100 W, better than the state-of-the-art frequency-selective limiters.

Keywords— Absorptive, interference, microplasma, notch filter, power limiter.

I. INTRODUCTION

High-power microwaves and electromagnetic pulses are instantaneous, intense energy field threats that can potentially damage electrical systems and disrupt communications. An effective protection scheme to counteract it is a reconfigurable frequency-selective limiter (FSL) in the front end that can operate over safe frequency bands and shut off a frequency window that encounters a high power threat. The architectures proposed over the recent years to solve this problem can broadly be categorized based on utilizing diode, thin film, ferrite, multiplexers, or absorption techniques.

Power limiters using PIN diodes [1], [2] have tunable limiting power threshold and low passband insertion loss but introduce a wideband rejection and can only handle low input powers. Thin film limiters based on vanadium dioxide (VO_2) [3], [4] rely on phase transition from the “insulator state” to the “metallic state” when the input signal reaches a certain threshold. While the passband loss in these devices is low, the stopband is not tunable. Ferrite-based FSLs [5], [6] operate based on the idea of coupling higher magnitude input signals into spin modes of narrow bandwidths to dissipate them. But they are bulky, have high passband loss and longer response times, making them infeasible for emerging radars and electronic warfare applications. Continuous-channel double multiplexer FSLs [9] are based on switching between different paths of coupled microwave resonators to achieve frequency selectivity. However, they suffer several drawbacks, such as low power handling, due to the presence of solid-state switches, bandwidth, and limited isolation. Triple-mode filter

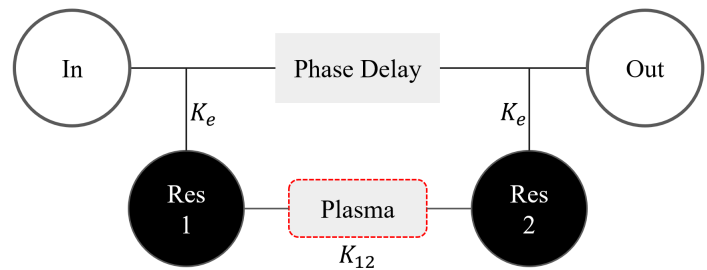


Fig. 1. The topology of the proposed plasma-based frequency-selective absorptive Limiter.

FSLs [10] rely on switching between all-pass to absorptive bandstop modes. Their major drawback is that they dissipate a considerable portion of the input power due to their high all-pass loss and the system requires a feedback control loop which adds more complexity.

Plasma limiters in both resonant and wideband forms have attracted much attention as plasma can handle very high powers and is not sensitive to harsh environmental conditions [11]–[14]. However, plasma is a lossy and dispersive medium; therefore, plasma limiters typically suffer from a non-selective and low-isolation performance. This paper introduces a novel high-power plasma-based FSL in which a phase relationship allows for destructive interference during the high input power threats to achieve deep and selective isolation. Conversely, the limiter allows for constructive interference when the plasma is OFF at low input powers, which levels with minimal loss. The theory of this frequency-selective plasma limiter, along with the simulation and measurement results, are discussed in this paper.

II. THEORY OF ABSORPTIVE PLASMA FSL

Absorptive filters are a relatively new class of bandstop structures that can obtain high isolation using low-quality-factor resonators [15], [16]. The coupling coefficients in absorptive filters depend on their physical characteristics; hence, the filter response, by definition, is not a function of input power. To design a plasma-based FSL, the topology of an absorptive filter was modified by integrating a plasma cell in the inter-resonator coupling structure, as depicted in Fig. 1. Thus, the inter-resonator coupling, K_{12} , changes between the low-power (plasma-OFF) and high-power (plasma-ON) modes. The dielectric properties of plasma are stated below, showing their dependence on plasma electron number density, pressure, gas type, and

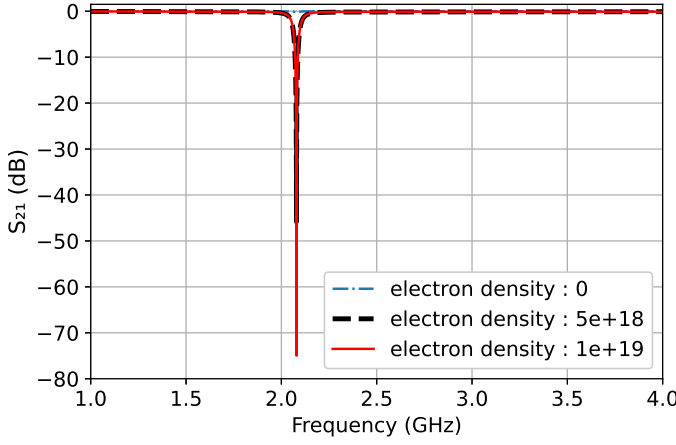


Fig. 2. Theoretical analysis of the proposed FSL showing the transmission coefficient switches between all-pass to a bandstop response by plasma generation. A plasma density closer to the optimum value for destructive interference results in higher isolation.

frequency [17]. Electron density inside the cell increases significantly when the plasma gets ON. This changes the plasma impedance, Z_p , and phase, θ_p , which changes the inter-resonator coupling K_{12} .

$$\epsilon_{rp} = 1 - \frac{e^2 n_e}{\epsilon_0 m (\omega^2 + v_m^2)}. \quad (1)$$

$$\sigma_p = \frac{e^2 n_e v_m}{m (\omega^2 + v_m^2)}, \quad (2)$$

The main idea is to design the structure to exhibit constructive interference when the input power is low, i.e., plasma OFF mode, leading to an all-pass response, and destructive interference when the input power exceeds the threshold of the gas breakdown power, i.e., plasma ON mode, leading to a bandstop performance. For theoretical design, the ABCD matrix of the entire structure was derived. Then, the S_{21} expression was optimized by considering plasma dimensions, gas pressure, phase delay, and external coupling coefficient (K_e) as optimization parameters. The goal was to maximize S_{21} when electron number density (n_e) is low (OFF mode) and minimize it at the resonant frequency when n_e is high (ON mode). The change in K_{12} was theoretically optimized to transition from constructive to destructive interference after plasma formation and hence from an all-pass to bandstop mode. The converged theoretical results of this analysis for one sample resonant frequency are presented in Fig. 2. An OFF-mode loss of 0.14 dB, high bandstop isolation of 75 dB, and a narrow FBW of 0.5% are observed.

III. MEASUREMENT RESULTS

A proof-of-concept plasma FSL was implemented on a 60-mil thick Rogers TMM4 substrate with quarter-wavelength microstrip resonators and a commercially available gas discharge tube (GDT) - Littelfuse SE140 with a breakdown voltage of 140 V. Figure 3 shows the fabricated device.

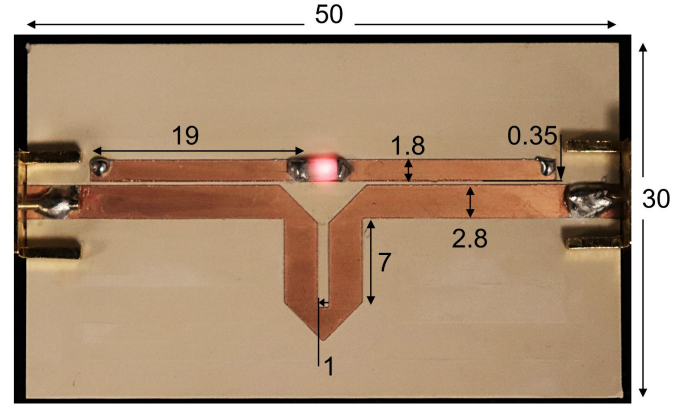


Fig. 3. A fabricated prototype of the Plasma based absorptive Frequency selective limiter (all dimensions are in mm).

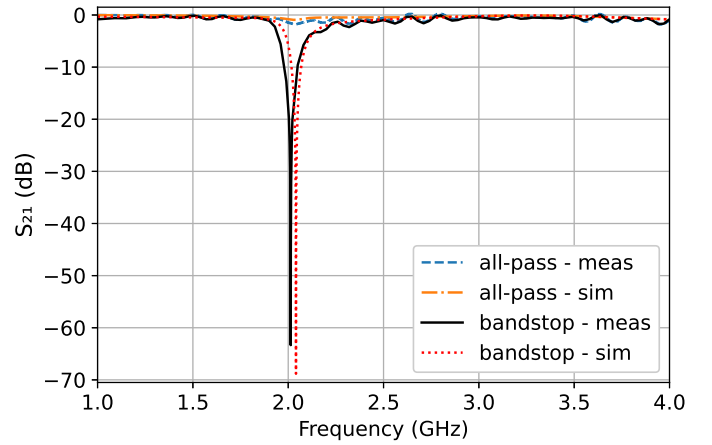


Fig. 4. Simulated and measured response of the limiter in both plasma OFF (low power) and plasma ON (high power) scenarios, showing a transition from an all-pass to a bandstop behavior.

The HFSS simulated and measured transmission coefficients of the designed plasma FSL are compared in Fig. 4. The simulations are performed by assuming plasma to be a lossy dielectric with EM properties dictated by (1) and (2). The all-pass measurement shown is with an input power of 25 dBm (0.3 W) and the bandstop measurement at 34.5 dBm (2.8 W). The HFSS simulated insertion loss is, however, less than 0.9 dB in the frequency band of 1 to 4 GHz. The measured all-pass insertion loss is below 1 dB everywhere except at the resonant frequency, which is 1.6 dB. The slight discrepancy is attributed to manual assembly errors because this is a phase-sensitive device. The bandstop isolation is over 60 dB in simulation and measurement, while the FBW is 2.8%, ensuring a very selective limitation.

Figure 5(a) shows the measured transmission coefficient at the resonant frequency of 2.013 GHz as a function of input power, P_{in} . This is the natural resonant frequency of the employed shorted microstrip resonators but can be tuned by the implementation of a varactor [15]. As seen, the transition from all-pass to bandstop modes happens at the threshold power (P_{th}) of 34.5 dBm. At this input power, gas breakdown

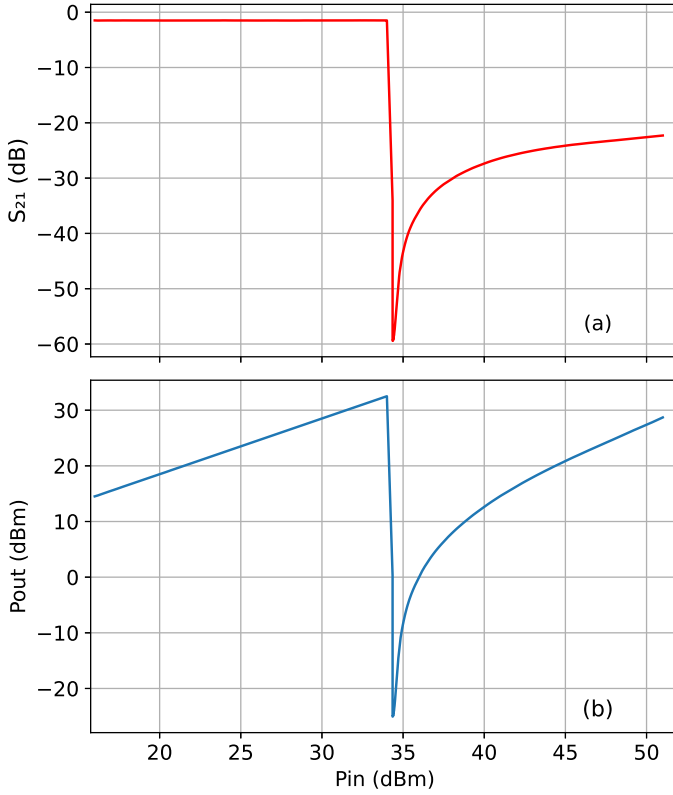


Fig. 5. (a) Measured transmission coefficient of the proposed plasma FSL at the resonant frequency of 2.013 GHz as a function of input power, clearly showing the transition from all-pass to a bandstop response. (b) Power limiting characteristic showing a minimal leakage power.

occurs, and the plasma impedance, Z_p , and consequently the inter-resonator coupling, K_{12} , change abruptly. The limiting threshold power can be tuned by applying a DC bias to the plasma cell for pre-ionization [14]. Since the destructive interference only lasts for a narrow range of K_{12} , the isolation reduces for powers higher than the P_{th} . Nonetheless, the plot of output power against the input power in Fig. 5(b) proves that the leakage power is always less than 1 W, which is sufficient for most applications.

A quantitative comparison of the proposed plasma limiter to the state-of-art FSLs is shown in Table I. It is seen that the proposed absorptive plasma FSL significantly outperforms in terms of power handling and isolation. The lower insertion loss was observed in the theoretical analysis when the resonators had higher quality factors. This can be achieved by replacing the low- Q planar microstrip resonators with high- Q ones, which is under investigation. Also, an effort is in progress to improve this limiter further by making it frequency and threshold power tunable, as discussed above.

IV. CONCLUSION

A novel plasma-based absorptive limiter was presented, demonstrating a selective isolation of over 60 dB and a power handling capacity of over 100 W, which are better than any other state-of-the-art FSLs. The structure is based on

Table 1. Comparison of the proposed plasma FSL to the state-of-art.

	Technology	Power (dBm)	Isolation (dB)	Loss (dB)
[2]	Diode	30	12	2
[4]	Thin film	43.5	16	1.6
[5]	Magnetic	35	11	4
[7]	Bandstop	20	18	2
[8]	MNRC	15	7.5	3.5
[9]	Multiplexer	38	22	1.8
[10]	Triple Mode	45	45	3.1
This work	Plasma	51	60	1.6

integrating a plasma cell within the inter-resonator coupling of an absorptive filter and designing the structure to achieve destructive interference in the presence of high input power, resulting in switching from a low-loss all-pass mode to a high-isolation bandstop mode. The insertion loss can be improved by using a higher- Q resonator. In addition, frequency and power tuning can be implemented for reconfigurability.

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