Abstract—The use of a power-dependent coupling structure that allows a cul-de-sac bandstop filter topology to continuously transform between a resonant all-pass response and a bandstop filter response with increasing input power is shown. In contrast to limiter devices that provide a wideband short circuit or ferrite resonance under high-power excitation, the concept presented in this paper provides the ability to design limiters with frequency-selectivity and without magnetic materials. For verification, a third-order power-dependent bandstop filter was designed and fabricated. It has a center frequency of 2.15 GHz, 3 dB bandwidth of 400 MHz, 1 dB limiting threshold of approximately 25 dBm, a response time of 10 ns, and provides over 16 dB of limiting.

Index Terms—Limiting, filters, resonator filters, microstrip filters, microwave filters.

I. INTRODUCTION

Sensitive RF and microwave systems often use limiters to protect their low-noise amplifiers and/or other front-end components from high-power interfering signals that would otherwise saturate or harm these components. Currently, system designers must choose between two broad categories of limiters, each with their own strengths and weaknesses. The first category is composed of PIN diode [1] and gas discharge [2] limiters. Such limiters can be made to exhibit low loss under low-power conditions, and their response is relatively fast. Under high-power conditions, limiters of this type become approximate short circuits and reflect incoming power. The bandwidth of the approximate short circuit is often several octaves if not decades of frequency. Therefore, even if an interferer has narrow bandwidth, this type of limiter severely compresses a receiver over its entire operating bandwidth whenever high-power signals of any bandwidth are present.

In contrast, ferrite limiters [3] produce narrowband bandstop responses at the frequencies of high-power interfering signals. Therefore, systems that use ferrite limiters are less compressed away from frequencies with high-power interference than systems that use the limiters described above. However, ferrite limiters are often very lossy (∼5 dB insertion loss [4]) over their entire operating bandwidth under low-power conditions, which reduces system sensitivity. In addition, ferrite limiters are not currently commercially available.

Limiter functionality has been incorporated into bandstop filters [5] to provide power-dependent notches. However, the limiter in [5] caused significant attenuation in bands adjacent to the bandstop center frequency when high-power signals were present. This paper presents an alternative bandstop-filter-based limiter concept that has low insertion loss under low-power excitation and a designable, narrow attenuation band when experiencing high-power signals in the designated band, as shown conceptually in Fig. 1 (a) and (b). Compared with previously-demonstrated limiters, the power-dependent bandstop filter (PDBSF) concept shown in this paper is more frequency selective than PIN diode limiters, faster, less lossy under small-signal excitation, and made with more-available materials than ferrite limiters, and has lower adjacent-band insertion loss than other bandstop filter approaches.

II. POWER-DEPENDENT BANDSTOP FILTER TOPOLOGY

Fig. 1 (c) shows a 3-pole cul-de-sac bandstop filter topology [6] with power-dependent coupling between resonators 2 and 3. The power-dependent coupling structure will be described in the next section. For the purpose of understanding the PDBSF topology, assume that the coupling structure between resonators 2 and 3 provides zero coupling under low-power excitation and the amount of coupling needed for a desired 3-pole cul-de-sac bandstop filter under high-power excitation. When only low-power signals are present, resonator 3 is effectively removed from the circuit. The remaining resonators and couplings in Fig. 1 (c) can be designed to have a resonant all-pass response [7] to provide a low-loss transmission path over a wide bandwidth. When a high-power signal appears in the bandwidth of resonators 1 and 2, resonator 3 becomes coupled to the circuit. The addition of resonator 3 upset the balance of the resonant all-pass circuit, and with proper design, a 3-pole bandstop response appears. In order to reduce the size of the PDBSF by having a shorter through line, the circuit in Fig. 1 (c) can be transformed into the circuit in Fig. 1 (d) [8], where 2φ is less than λ/4 electrical length. The tradeoff for the shorter through line in the design method in [8] is a larger required coupling magnitude from the through line to the resonator for a given filter response.

The topologies shown in Fig. 1 (c) and (d) are both reflection-mode topologies. While reflection-mode bandstop filters can have smaller size than other filter topologies, the maximum practical attenuation of a reflection-mode bandstop filter is limited to approximately 30 dB because it depends on impedance matching. However, this is not an issue in low-order PDBSFs because the minimum limiter diode on
resonance is a more significant cause of finite attenuation due to its lowering of the quality factor of some of the resonators in the filter. PDBSFs with different limiter diodes can be cascaded to increase attenuation. The topology in Fig. 1 (d) was chosen to demonstrate the PDBSF because of its small size and requirement for only one sign of coupling from the through-line to the resonators when \( \phi > 0 \).

III. POWER-DEPENDENT COUPLING STRUCTURE

In [9], a coupling structure that could provide significant or zero coupling between two resonators based on the state of a switch was presented. A schematic of the coupling structure is shown in Fig. 2 (a), and its coupling magnitude is plotted in Fig. 2 (b) vs. the ratio of capacitors \( C_1 \) and \( C_2 \) for a given even and odd mode impedance of the coupled lines. At a ratio of \( C_1/C_2 = 1 \) for this case, the coupling is reduced to zero over a theoretically infinite bandwidth. At other values of the ratio of \( C_1/C_2 \), coupling magnitudes relevant to narrowband filter responses result. The structure can be made to be power-dependent by using limiter diodes in place of the switches. With respect to Fig. 2 (b), the structure is designed for a PDBSF such that the zero coupling state occurs when the limiter diodes are turned on by RF power. When the diodes are off and only low-power signals are present, the effective \( C_1 \) is reduced due to the series combination of the diode capacitance and the physical \( C_1 \). Therefore, the coupling between the resonators increases to a designable value, which is a shift to the left in the plot in Fig. 2 (b).

IV. FREQUENCY-SELECTIVE LIMITER PROTOTYPE

Suspended stripline was used to implement the topology in Fig. 1 (d) for a PDBSF with a center frequency of 2.15 GHz and a 3-dB bandwidth of 400 MHz. 0.127-mm-thick Rogers 6202 (\( \epsilon_r = 2.90 \), \( \tan(\delta) = 0.0015 \)) was used as the substrate, and 1.5 mm of air dielectric was present between the substrate and the walls of the aluminum housing. A model of the prototype can be seen in Fig. 3 with relevant dimensions listed. The through line width was reduced from 4.2 mm (50 ohms) to 1.4 mm in the area of the filter for increased coupling, and matching at the ports was achieved by balancing the increased series inductance of the narrower line with the shunt capacitive loading of the resonators. Resonator 1 is coupled to the through line twice using overlapping metal from both sides of the substrate over 12.3 mm of through-line length, and resonator 2 is coupled to the through line once using another overlapping metal region.

A Skyworks CLA4607-000 limiter diode was used as the power-dependent element. Two lumped-element models of the diode were made using measurement data in low- and high-power states. The filter was then designed in both states concurrently to have all-pass and bandstop filter responses in the low- and high-power states, respectively. Capacitors \( C_1 \) and \( C_2 \) of the power-dependent coupling structure were designed using overlapping metal layers on the substrate.

V. MEASURED RESULTS

The PDBSF prototype was measured using a Keysight N5222A network analyzer. The swept-frequency signal from the network analyzer was amplified by an Ophir 5263FE power amplifier, input to the PDBSF, attenuated by 40 dB, and returned to the second port of the network analyzer. Isolators were used to protect the network analyzer and power amplifier from unwanted signals. Measured transmission through the circuit can be seen in Fig. 4 for a range of input signal powers.
The S parameters of the PDBSF under excitation by 10 dBm are shown in dashed and dotted traces for the frequency range of 10 MHz to 7.5 GHz. The response is similar for all powers below 10 dBm. The passband is moderately-well matched up to 7 GHz. Above 7 GHz, a spurious mode degrades the upper passband. Limiting measurements are shown with solid traces over a frequency range of 1 GHz to 4.5 GHz due to the bandwidth limitation of the power amplifier. Note that the power amplifier noise and changing impedance with power, as well as network analyzer calibration through high attenuation, cause the passband response to have more ripple in the high-power data. The network analyzer was calibrated when the power amplifier output power was 10 dBm. The 1 dB limiting threshold is approximately 25 dBm, and over 16 dB of limiting is provided when input power is high.

Leading-edge and trailing-edge pulse limiting measurements can be seen in Fig. 5. These measurements used a signal generator and a power combiner to combine 4.7 μs pulses of a 2.15 GHz carrier with the swept frequency signal from the network analyzer. The combined signal was input to the PDBSF, attenuated by 33 dB, and fed into a Keysight DSO-X 91604A oscilloscope. The black traces show the pulse through the PDBSF when limiting was disabled by severing the ground return path for the diode. The red traces show the pulse through the filter while limiting was enabled. At the leading edge of the pulse, the full power never gets through the filter. Limiting starts at 10 ns after the limiting threshold is surpassed, and it takes approximately 200 ns to reach a steady-state limiting value. At the trailing edge of the pulse, the filter does not ring for a significant amount of time, allowing low-power signals to pass with low attenuation almost immediately after the high-power signal subsides.

VI. CONCLUSION

Power-dependent bandstop filters allow for fast limiting over narrow bandwidths. Such circuits could be used to protect sensitive receivers from high-power signals whose frequency is known but schedule is not while allowing the receiver to operate at other frequencies with high sensitivity.

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REFERENCES

[8] Redacted. This reference is accepted for publication, but it is not yet published. A full citation will be included in the final version if this paper is accepted.

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