Broadband Microwave Frequency Selective Limiters

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Abstract

This paper presents a novel design for frequency selective limiters based on reflection-mode nonlinear bandstop filters. This technique permits the use of low-Q lossy resonators for high-Q bandstop filter application. This type of frequency selective limiter achieves fast switching, high-level of power limiting, and flexible channel bandwidth. The prototype of the third-order device indicates 2 dB insertion loss for low RF powers. At high RF powers, it demonstrates 18 dB limiting level, 3 dBm limiting threshold, and 200 MHz limiting bandwidth. The switching speed is less than 10 ns, thus the spike leakage is minimized. The single-channel circuit has high return loss, so its cascade version is used to realize multi-channel frequency selective limiters for wideband operation.

Introduction

Limiters are often used at the front-end of microwave receivers to protect sensitive circuitry against large interfering signals. Some conventional limiters make use of shunt PIN diodes placed before the receivers. However, PIN limiters cannot discriminate the received signals in terms of frequency. They respond to the total rf power, attenuating all signals when the accumulative powers exceed the limiting threshold. Thus limiting the magnitude of large signals also attenuates the wanted small signals, with a consequent reduction in sensitivity. For wideband microwave receivers, they are required to operate in wideband channel, and intercept multiple signals with wide dynamic range. Problems arise when it is needed to identify a small signal in the present of large interfering signals. In this situation the receivers encounter desensitization and low probability of intercept.

The Frequency Selective Limiters have long been desired to solve all those problems. The basic operation of ideal FSLs is illustrated in Figure 1. They are designed to limit signals at individual frequencies independently. One FSL channel compresses only a large signal at one particular frequency, but passes other signals without attenuation. The above-threshold signals are limited proportional to their amplitudes. The resulting output spectrum contains signals of relatively equal amplitudes, and low dynamic range. Successful implementation of this device will contribute a significant improvement to the wideband receivers.

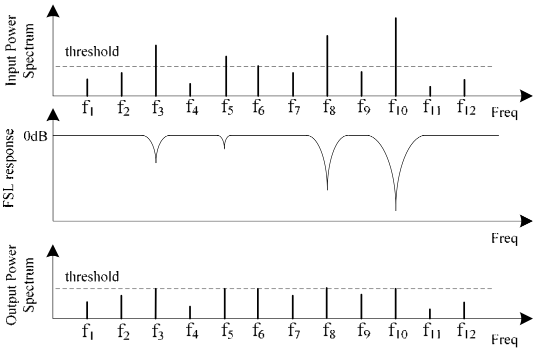


Figure 1: Basic operation of a Frequency Selective Limiter.

Generally, FSLs can be divided into two main groups, lumped FSLs and ferrite FSLs

The developments of ferrite-based FSLs were extensive. Many researchers have reported the performance and characteristic of their devices [1]-[7]. However, there was no obvious evidence of prior research on circuit-based FSLs.

This paper presents a novel method of realizing high-performance lumped FSLs. The technique used is based on the design of reflection mode nonlinear bandstop filters. This configuration allows high-Q bandstop filters to be constructed using low-Q lossy resonators. The nonlinear bandstop filter is basically a bandstop resonator loaded with a diode. Its key concept is built on the fact that the diode's resistance can be controlled by the RF power level. Therefore, its response can vary from all-pass to bandstop depending on RF power levels. This technique achieves low insertion loss, flexible channel bandwidth and center frequency, low spike leakage, and high level of power limiting. In the following sections, the fundamental concept of lumped FSLs is presented. Then, the first-order and third-order FSLs are presented together with their design and experimental results.

Basic FSL circuits

A simple FSL is represented by a lumped LC circuit shown in Figure 2. It consists of two main elements, a bandstop resonator and a diode limiter. This combination enables the circuit to selectively limit signals at a particular frequency. The RF choke (RFC) is used for diode self-biasing. The bias current is derived from rectified RF signals

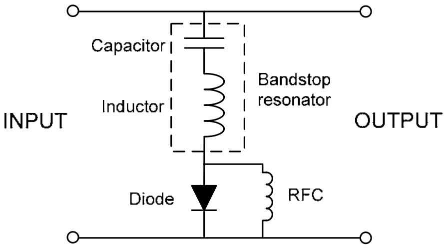


Figure 2: A lumped LC Frequency Selective Limiter.

The operation of this circuit can be divided into two modes, bandstop and all-pass. The bandstop mode occurs when a large signal at the resonant frequency is input to the circuit. At resonance, the series resonator has theoretically zero impedance. The stopband attenuation depends on the resistance of the diode, controlled by RF power levels. At high power levels the diode resistance is low, and the stopband attenuation is relatively high. At low power levels the diode resistance is high; consequently the stopband attenuation is low. The second mode of operation is all-pass mode. It occurs when signals at other frequencies are input to the circuit. Regardless of RF power levels, the series resonator presents high impedance. The circuit is now open-circuited, so the small signals can pass without attenuation.

Design of FSL circuits

The lumped FSL circuit in Figure 2 suffers from losses embedded in the resonator and added by the diode. Thus, the resulting FSL circuit has relatively low Q. This drawback makes the lumped circuit less attractive for the frequency selective limiting application. This problem can be overcome by using a reflection mode concept [8], shown in Figure 3(a). Basically, the transmission coefficient (S_{12}) of the overall device is derived from a reflection function (S_{11}) of the sub-networks. If the sub-networks are designed such that they are purely reflective, all signals from the input are transferred to the output. Then, all-pass response is achieved. On the other hand, if they are designed such that signals are critically coupled to the sub-networks, there is no reflected signal to the output, then achieving theoretically infinite attenuation.

Based on this technique, two identical lumped FSL sub-networks, Figure 3(b), are connected to the output of a 3-dB 90° branch line coupler as illustrated in Figure

3(a). Effectively, this configuration enhances the total Q of the circuit [9].

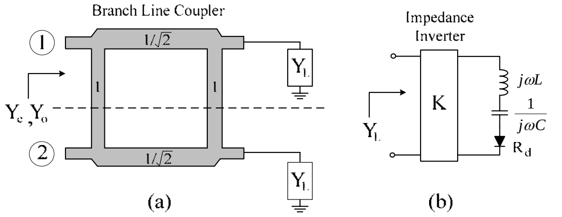


Figure 3: (a) A reflection mode FSL (b) An FSL sub-network.

Even and odd-mode transfer matrix of an unloaded branch line coupler can be written as;

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & j \\ j & -1 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \tag{2}$$

Y_e and Y_o of a branch line coupler loaded with sub-networks having input admittance of Y_L are;

$$Y_e = \frac{DY_L + C}{BY_L + A} = \frac{j - Y_L}{jY_L - 1} \tag{3}$$

$$Y_o = \frac{jY_L - 1}{j - Y_L} = \frac{1}{Y_e}. \tag{4}$$

For a symmetrical two-port network. S-parameters are;

$$S_{11} = \frac{1 - Y_o Y_e}{(1 + Y_o)(1 + Y_e)} \tag{5}$$

$$S_{12} = \frac{Y_o - Y_e}{(1 + Y_o)(1 + Y_e)}. \tag{6}$$

From (4), $Y_o = 1/Y_e$, thus

$$S_{11} = 0. \tag{7}$$

Then, the network is perfectly matched, and

$$S_{12} = \frac{Y_o - Y_e}{(1 + Y_o)(1 + Y_e)} = \frac{(1 - Y_L)(j + 1)}{(1 + Y_L)(j - 1)}. \tag{8}$$

For a first-order limiter, Y_L is implemented using a network shown in Figure 3(b). Assuming K=1 of the impedance inverter,

$$Y_L = R_d + j\omega L - \frac{j}{\omega C}, \tag{9}$$

where R_d is a diode resistance. Hence,

$$|S_{12}(j\omega)|^2 = \frac{(1 - R_d)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}{(1 + R_d)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}. \tag{10}$$

For *low* RF power, R_d is high. Then,

$$|S_{12}(j\omega)|^2 \approx 1, \tag{11}$$

which is an *all-pass* response.

For *high* RF power, R_d is low. Assuming $R_d = 1$,

$$|S_{12}(j\omega)|^2 = \frac{1}{1 + \frac{4}{\left(\omega L - \frac{1}{\omega C}\right)^2}}, \tag{12}$$

which is a *bandstop response*.

The prototype of the first-order FSL is shown in Figure 4. The capacitors were realized by interdigital capacitors. The inductors were realized by inductive short-circuited stubs. The schottky diodes were placed in series between these two components. This arrangement inherently provides dc blocks. The dc return paths were realized by quarterwave length short circuit stubs. The circuit was constructed on a substrate, with dielectric constant of 2.2, and a thickness of 0.787 mm.

High-order FSL circuits can be achieved by redesigning the first-order sub-network in Figure 3(b). The designs of high-order sub-networks with decreasing-Q resonators are described in [10]. For an equiripple response third-order sub-network, its S_{11} can be written as;

$$S_{11}(p, \alpha) = \prod_{r=1}^{n} \left[\frac{(p\alpha - j\cos\theta_r)}{\left(p\alpha - j\cos\left(\cos^{-1}(\alpha) + \theta_r\right)\right)} \right] \tag{13}$$

where; $\theta_r = \frac{r\pi}{(n+1)}$ (14)

α is a constant which determines the ripple level,

n is the order of the sub-network.

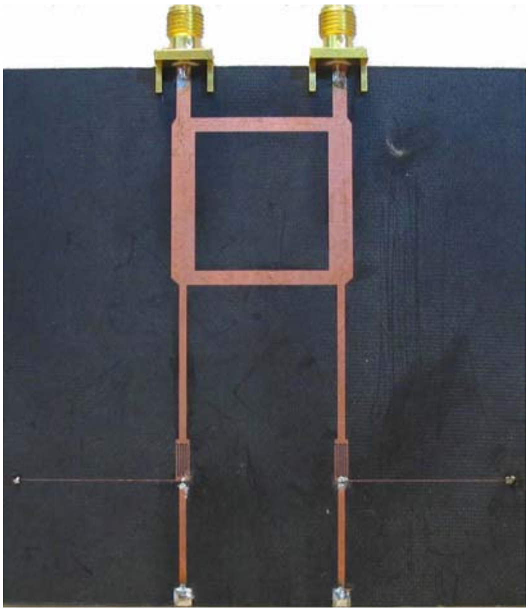


Figure 4: A prototype of a first-order FSL.

The input admittance of the reflection-mode sub-network can be written as,

$$Y_L(p) = \frac{1 - S_{11}(p)}{1 + S_{11}(p)} \qquad (15)$$

To give a 3rd order response with 30 dB ripple level, n = 3 and α =1.83. By applying (13), the S_{11} of the sub-network is;

$$S_{11}(p) = \prod_{r=1}^{3} \left[\frac{\left(1.83p - j\cos\frac{r\pi}{4}\right)}{\left(1.83p - j\cos\left(\cos^{-1}(1.83) + \frac{r\pi}{4}\right)\right)} \right]$$

Then, the input admittance of the sub-network is,

$$Y_L(p) = \cfrac{0.93^2}{0.83p + 0.14 + \cfrac{1.032^2}{2.06p + 0.5 + \cfrac{1.18^2}{2.34p + 1.4}}}$$

and the circuit is shown in Figure 5.

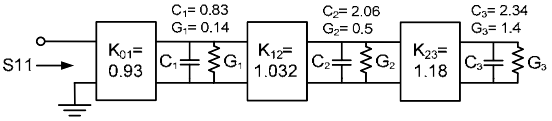


Figure 5: A third-order sub-network.

The third-order sub-network in Figure 5 is incorporated in the reflection-mode configuration. The prototype of the resulting circuit is shown in Figure 6.

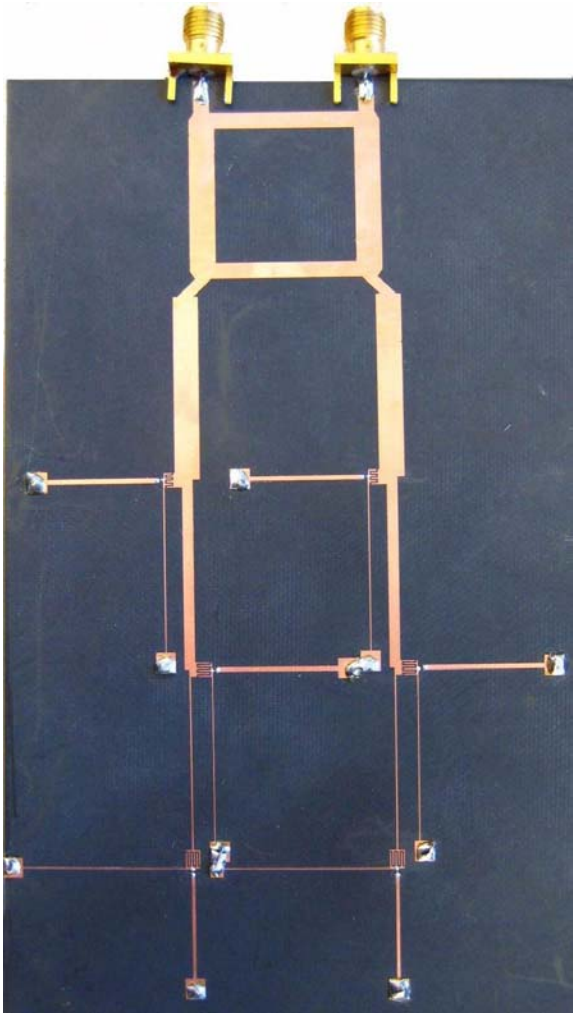


Figure 6: A prototype of a third-order FSL.

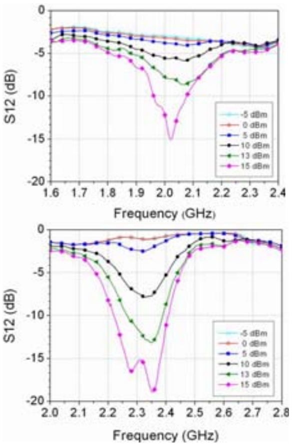
Experimental Results

To establish the fundamental characteristics of this new type of frequency selective limiters, the following measurements were performed.

1) Transmission response (S12): The prototype has demonstrated the frequency selective limiting behaviours as shown in Figure 7. The response varied with the RF power levels. For low power levels, the circuit gave a near all-pass response with some insertion loss. For high power levels, the circuit produced a bandstop response with the stopband attenuation increasing with the RF power levels. For the first-order prototype, its limiting threshold was measured at 0 dBm. The maximum attenuation was seen at 15 dB, and the limiting bandwidth was 300 MHz. For the third-order prototype, its limiting threshold was measured at 3 dBm. The maximum attenuation was seen at 18 dB, and the limiting bandwidth was 200 MHz. It was obvious that the selectivity and stopband attenuation were increased with the order of the sub-networks.

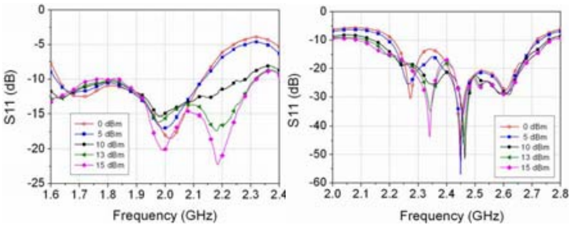
2) Reflection response (S11): The measured results in Figure 8 were shown that the return loss of the circuit was better than 10 dB and 15 dB, for the first-order and third-order FSLs respectively, across the working frequencies. This was agreed with the mathematical prove in (7), which implied that the input and output of the circuit were matched. Therefore, more FSL modules can be cascaded for wideband operation.

3) Transient response: This circuit is designed to operate in wide band receivers such as ESM receivers. This type of receivers may be used to intercept RF pulse signals. Thus, it is important to measure the transient response of the circuit. The rising and falling time of the devices were shown in Figure 9 and 10, and were measured at 15 ns and 25 ns, for the first-order circuit, and 10 ns and 30 ns, for the third-order circuit respectively. This implies that, for the third-order case, the pulse that is shorter than 10 ns will not be limited, and hence overload the receiver making it unable to detect the desired signals. This effect is called spike leakage. Its recovery time was 30 ns, so the small signal that is received within 30 ns after a big pulse will be attenuated. Due to the deployment of fast switching diodes, the problems of spike leakage and recovery time were measured to be far less than other types of FSLs.



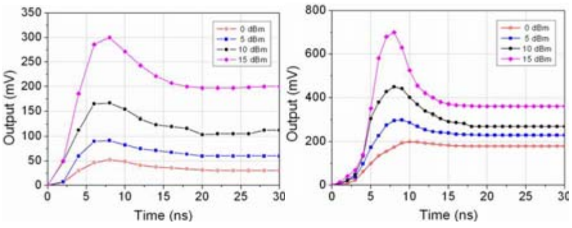
(a) (b)

Figure 7: Transmission response (S_{12})
(a) a first-order FSL
(b) a third-order FSL.



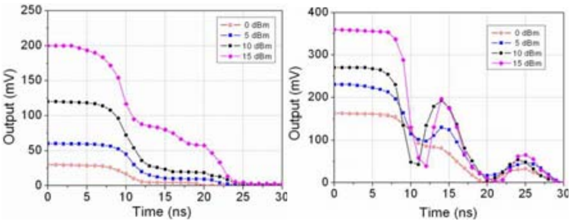
(a) (b)

Figure 8: Reflection response (S_{11})
(a) a first-order FSL
(b) a third-order FSL.



(a) (b)

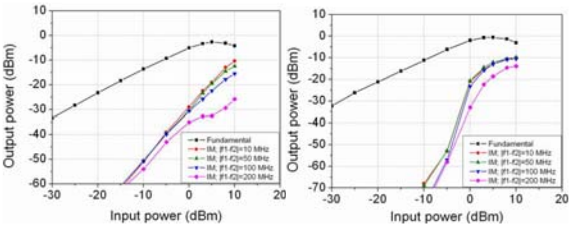
Figure 9: Rise time
(a) a first-order FSL
(b) a third-order FSL.



(a) (b)

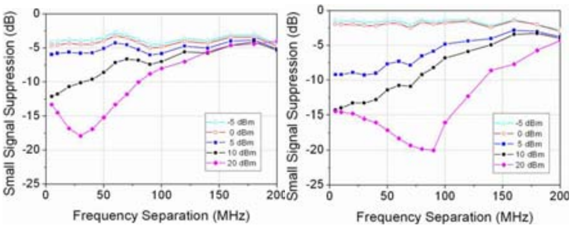
Figure 10: Fall time
(a) a first-order FSL
(b) a third-order FSL.

4) Intermodulation distortion: FSLs are nonlinear circuits, so intermodulation distortions are inevitable. Intermodulation products are generated when two or more signals are input to the circuit. In this experiment, a fundamental signal was input at the center frequency of the channel. Another signal was input at a specific frequency separation; 10, 50, 100 and 200. The relationship between input and output powers of the fundamental and intermodulation signals were plotted in Figure 11. From the experiment, the output of the fundamental signal was linear at low input power. It became saturate when the input power was higher than the limiting threshold. At low RF powers, the intermodulation powers were as low as the noise level. As the RF power increased, the intermod increased rapidly. However, the intermod decreased as the frequency separation increased. It was seen that the intermod increased with the order of the sub-networks.



(a) (b)

Figure 11: Intermodulation distortion
(a) a first-order FSL
(b) a third-order FSL.



(a) (b)

Figure 12: Small signal suppression
(a) a first-order FSL
(b) a third-order FSL.

5) Small signal suppression: When the FSL limits a large signal, it produces a bandstop response around the center frequency. This behaviour leads to the suppression of nearby small signals. This experiment investigated the extent of signal suppression when a small signal was input closed to the center of limiting channel. In this test, a fundamental signal was input at the center frequency with swept powers. Another small signal was input at -10 dBm with varying frequency separation. From Figure12, the low-power fundamental signals did not create significant suppression to the small signal. At high-power fundamental signals, the small signal experienced more attenuation as they approached to the center frequency.

Conclusions

A new approach is proposed for improving interference cancellation in wideband receivers using a bandstop resonator incorporating a Schottky diode. The technical approach is flexible in terms of center frequency, bandwidth, and limiting level. The single-channel limiter has shown the frequency selective limiting behaviour with high limiting level and low insertion loss. Its extensive fundamental data such as S-parameter, multiple signal characteristic, and time response were presented. More work can be done towards miniaturization and MMIC integration. The circuit compresses large signals while maintaining the strength of small signals. A significant reduction in the signal dynamic range can be achieved. This type of dynamic range compressor has potential application in Electronic Support Measures for Electronic Warfare Systems.

Acknowledgements

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