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W-band sharp-rejection bandpass filter with notch cavities

Chen Zhenhua Xu Jinping

(State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China)

Abstract: High-Q notch cavities combined with a low-order E-plane fin-line filter are used for designing a sharp-rejection band-pass filter (BPF) at W-band. Based on the conventional E-plane fin-line structure, an E-plane extended cavity is implemented to enhance the suppression at unwanted frequency points near the passband. The passband performance is not disturbed and the whole structure remains simple to be assembled. To extend the suppression bandwidth, two separated notch cavities are designed and arranged at the input and output ends of the fin-line filter, respectively. A prototype BPF is fabricated and measured. Experimental results show that the minimum insertion loss is 2.7 dB over a passband of 1 GHz. The suppression is about 85 dB near 91.7 GHz, which is 2.2 GHz lower than the center frequency. Experimental results agree well with simulation.

Key words: W-band; E-plane filter; sharp rejection; notch filter

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E-plane waveguide filters have been widely used at millimeter-wave frequencies for realizing low insertion loss, low cost and mass producible microwave configurations [1-4]. While used in electronic systems operating at higher millimeter-wave frequencies, the functional modules of the systems are usually assembled with waveguide interfaces, so these kinds of filters are easy to be integrated with other components without any further transition structures.

In a heterodyne receiver system, isolation between the radio frequency (RF) and the local oscillator (LO) is critical to the sensitivity and dynamic range of the receiver. High-isolation performance is usually realized by a filter with a high stopband suppression level. Furthermore, many multi-channel or diplexer applications require filters with sharp cut-off characteristics. To increase the steep attenuation slope, positioning transmission zero close to the cut-off frequency is more convenient than increasing the order of the filter, which will increase the size and insertion losses. In Ref. [5], a folded cross-coupling configuration is adopted to produce transmission zeros and the out-of-band rejection performance can be locally improved by selectively positioning transmission zeros. In Ref. [6], a 3-order E-plane filter compatible with the split-block housing E-plane topology is proposed to produce sharp higher frequency roll-off by implementing a transmission zero. However, these involved structures are metal-insert E-plane filters which are difficult to machine precisely at W-band (75 to 110 GHz).

Although E-plane fin-line filters have higher machining precision than the metal-insert type, they are still difficult to suppress the frequency points which are very close to the passband [7]. To achieve better sharp-rejection performance, higher order fin-line filters are required, which will bring more loss and an unrealistic metal strip width. In this paper, we present a low-order E-plane fin-line filter with sharp-rejection characteristics, in which the transmission zeros are introduced by high-Q notch cavities cascaded with the fin-line structure. By properly choosing the dimensions of the resonators and optimizing the coupling between the cavities and the fin-line structure, the suppression level at the unwanted frequency points near the passband can be greatly improved without disturbing the passband performance. The measured results present good sharp-rejection characteristics while maintaining low cost and simple structure.

1 Notch Mechanism and Coupling Effects between Fin-Line Filter and Notch Cavity

As required by a specific application, a 93.9 GHz center frequency, a 1 GHz passband bandwidth, a less than 3 dB passband insertion loss and a more than 75 dB suppression from 91.6 GHz to 91.8 GHz are specified for the filter design.

The proposed filter is composed of a 5-order E-plane fin-line filter and high-Q notch cavities. The notch mechanism and the coupling effects between the fin-line filter and the single-notch cavity are investigated. The final prototype filter is fabricated with double-notch cavities, which will be demonstrated in section 2.

The design approach of the conventional fin-line filter proposed by Konishi [8] is relatively mature and adopted in our filter design. The fin-line structure is realized with a standard WR10 waveguide ($a = 2.54$ mm, $b = 1.27$ mm) and a 5-mil-thick RT/Rogers 5880 substrate ($\varepsilon_r = 2.2$). Its layout and dimensions are summarized in Fig. 1 and

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Biographies: Chen Zhenhua (1984—), male, graduate; Xu Jinping (corresponding author), male, doctor, professor, jpxu@seu.edu.cn.

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Tab. 1, respectively.

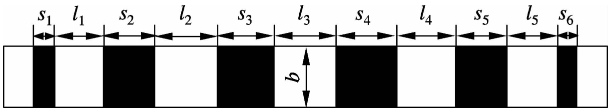

Fig. 1 Layout of the fin-line structure

Tab. 1 Dimension of the fin-line structure mm

$s_1 = s_6$	$s_2 = s_5$	$s_3 = s_4$	$l_1 = l_5$	$l_2 = l_4$	l_3
0.38	1.43	1.56	1.41	1.42	1.43

The notch characteristic is introduced by a high-Q cavity resonator [9], which is shaped by two-side step E-plane extensions of a standard rectangular waveguide. The extension section is designed as a dual mode cavity, which supports the first and the second distinct electromagnetic modes of propagation. The dual mode cavity has a cut-off frequency less than the operating frequency f_0 for the second mode, while the WR10 waveguide has a cut-off frequency greater than f_0 for the second mode. Its partial view is depicted in Fig. 2.

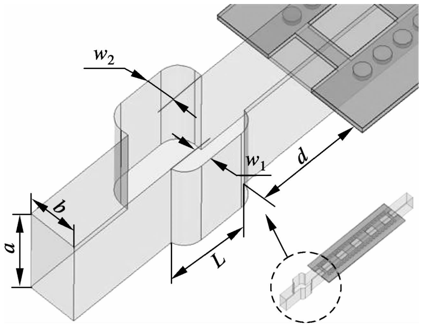

Fig. 2 Partial view of the single-notch cavity

As the incident wave in the form of the fundamental mode TE_{10} propagates into the extension section, a part of this mode will be converted into the second higher mode TE_{11} (Here, the simplest case is considered, so the degenerate mode of TE_{11} and the other higher order modes are not explained in detail). Upon reaching the other end of the dual mode cavity, most of the energy in the second mode will be reflected back through the dual mode section, while a small portion will be reconverted into the field pattern of the first mode. By adjusting the parameters of the dual mode section, it may be made resonant at f_0 in the second mode, and that portion of the second mode at f_0 which is reconverted into the first mode will be precisely equal in amplitude and oppositely phased to that portion of the wave energy at f_0 which has remained in the form of the first mode. Thus, transmission at f_0 in the first mode is nullified. It is noteworthy that the conversion from TE_{11} to TE_{10} will not occur while the extension is symmetric, i. e., $w_1 = w_2$. This can be concluded from the Fourier transform of the incident wave in the form of TE_{10} that, the second mode TE_{11} will not exist in the expansion equation when the extension section is symmetric, therefore, the coupling between the first mode and the second mode is absent.

Fig. 3 gives the variations of notch frequency (frequency corresponding to maximum reflection) vs. different combinations of w_1 and w_2. It can be found that notch frequency decreases as $w_1 + w_2$ increases, and the singular points exist when $w_1 = w_2$, which is due to the absence of coupling.

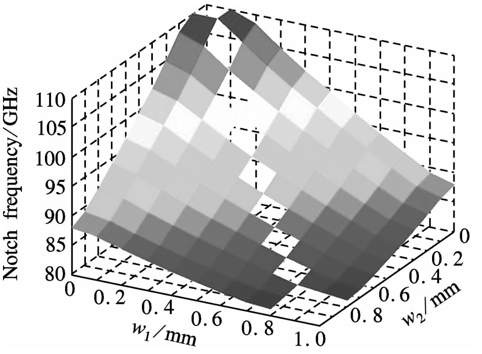

Fig. 3 Variations of notch frequency vs. different w_1 and w_2

The initial values of the notch cavity are chosen as follows: $L = 2.15$ mm, $w_1 = 0.5$ mm, $w_2 = 0.75$ mm. Thus, the resonant frequency f_r of the second mode TE_{11} is 91.7 GHz, and the unloaded quality factor Q of the notch cavity is 3 750. When the high-Q notch cavity is cascaded with the fin-line structure, which implies that the cavity is loaded, its quality factor Q becomes a loaded quality factor Q_L, and it can be estimated by

$$\frac{1}{Q_L} = \frac{1}{Q} + \frac{1}{Q_{\text{fin-line}}}$$

where $Q_{\text{fin-line}}$ is the quality factor of the fin-line filter structure. The distance between the cavity and the fin-line structure is defined as d. At higher millimeter-wave frequencies, discontinuities between the fin-line filter and the notch cavity are significant, which may have great effects on the filter performance. Therefore, the interaction between the notch cavity and the fin-line filter is investigated to avoid performance degradation.

As shown in Fig. 4, Q_L and the notch frequency change slightly with the increase in d. This means that the notch frequency is relatively independent of the coupling between the cavity and the fin-line filter. It is mainly determined by the dimensions of the notch cavity. In addition, Q_L decreases greatly compared to the unloaded Q, and this may decrease the suppression at the notch frequency to some degree. Fig. 5 shows the insertion loss over the passband and the suppression at the notch frequency (91.7 GHz) for different d. It can be found that both in-band and out-of-band performance have a great relationship with the value d. In order to maintain the whole structure compact, d should be as small as possible, but too small a d will lead to serious higher order modes interaction, which will decrease the filter performance.

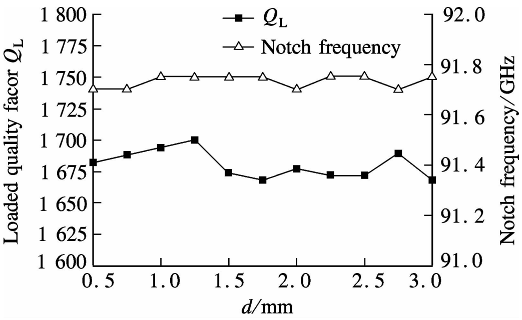

Fig. 4 Loaded quality factor and notch frequency for different distances between notch cavity and fin-line structure

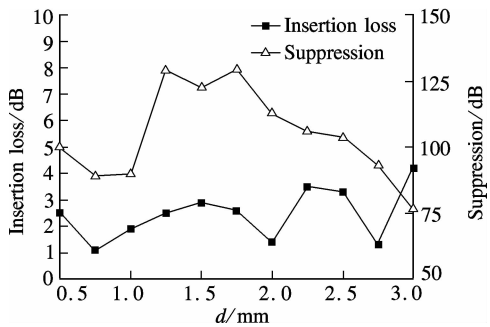

Fig. 5 Maximum insertion loss in passband and suppression at notch frequency for different distances between notch cavity and fin-line structure

An optimization is implemented to achieve the technical requirements of the filter and the compact structure size simultaneously, and $d = 2$ mm is chosen for the subsequent design.

Based on the above analysis, a conventional five-order fin-line bandpass filter integrated with a single notch cavity is simulated with Ansys HFSS. Its structure is depicted in Fig. 1. Fig. 6 shows the comparison of the simulated results of two filters: the conventional E-plane fin-line filter and the proposed filter with a single-notch cavity. It is clearly shown that a notch point is introduced by the proposed single-notch filter, and the suppression at 91.7 GHz and the sharp-rejection performance are greatly improved compared with the conventional filter without disturbing the passband performance.

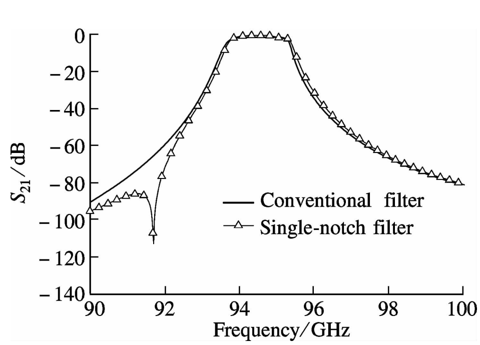

Fig. 6 Comparison results of two type filters

2 Design of Band-Pass Filter with Dual Notch Cavities

As depicted in Fig. 6, the notch bandwidth is relatively narrow due to the inherent attributes of the notch cavity, and the frequency offset is sensitive to the machining precision of the notch cavity at W-band. This can be clearly observed from Fig. 3. Therefore, sufficient surplus of the notch bandwidth should be reserved to prevent that the desired notch frequency 91.7 GHz deviates out of the notch band. So another notch cavity is added to the former single-notch filter to introduce another notch point and broaden the notch bandwidth. Fig. 7 shows a partial view of the proposed double-notch filter.

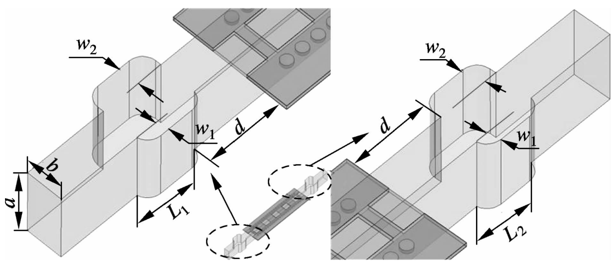

Fig. 7 Partial view of the double-notch filter

These two notch points are designed to deviate properly in order to further extend the notch bandwidth. Instead of cascading the two cavities directly, they are arranged at the input end and output end of the E-plane fin-line filter, respectively. This arrangement can avoid the appearance of spurious Bragg resonances which may occur when the two notch cavities are cascaded directly [10].

The expansion width of the second notch cavity is the same as that of the first one. The lengths of the two cavities L_1 and L_2 are adjusted to produce two separated notch frequency points to obtain the desired notch bandwidth. Fig. 8 shows the suppression performance of the double-notch filter for different L_2. L_1 is fixed to 2.1 mm, so its associated notch frequency is about 91.9 GHz. As L_2 becomes larger, the corresponding notch frequency decreases gradually, and the two notch points will overlap when $L_1 = L_2 = 2.1$ mm. The greater the difference between L_1 and L_2, the broader the notch bandwidth. All the dimension parameters are summarized in Tab. 2.

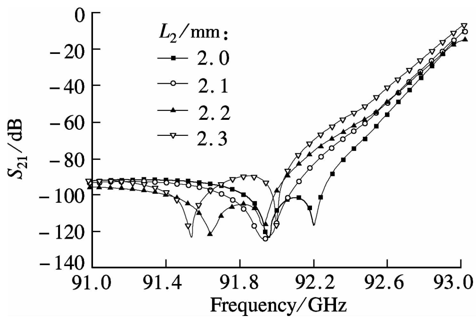

Fig. 8 Simulated suppression of the notch band for different values of L_2 ($L_1 = 2.15$ mm)

Tab. 2 Dimension of the double-notch cavity mm

w_1	w_2	L_1	L_2	d
0.4	0.7	2.1	2.2	2.0

3 Experimental Results

The above mentioned double-notch filter has been fabricated and measured. Fig. 9 shows the fabricated waveguide block of the bandpass filter. The 5-order fin-line filter is inserted along the E-plane of the waveguide block, and the two notch cavities are shaped by the E-plane extension of a standard WR10 waveguide.

Fig. 9 Fabricated W-band bandpass filter

Measured results depicted in Fig. 10 are obtained by a frequency extended Agilent N5254A vector network analyzer (VNA). The minimum measured insertion loss in the passband is 2.6 dB and the return loss is greater than 10 dB from 93.5 to 94.5 GHz. The suppression at 91.7 GHz is more than 85 dB. It can be found that there is some difference between the measured and the simulated

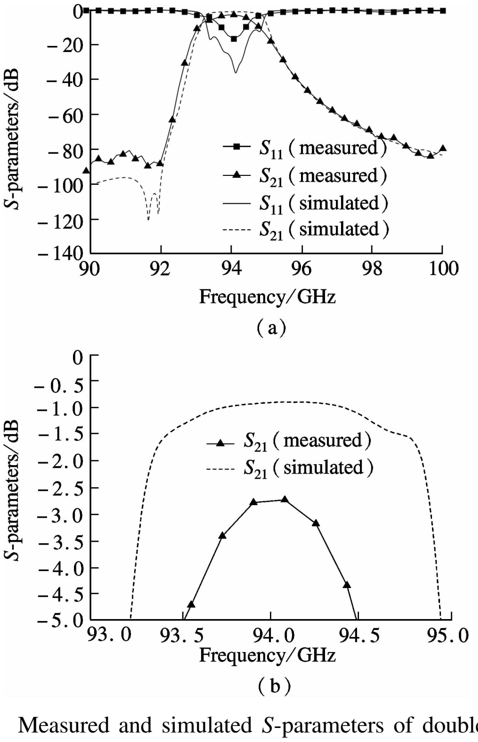

Fig. 10 Measured and simulated S-parameters of double-notch filter. (a) S-parameters across 90 to 100 GHz; (b) Detailed information of the insertion loss

suppression near 91.7 GHz. This is partly introduced by the limited dynamic range of the VNA operating in this frequency band and the misalignment of assembly.

4 Conclusion

A W-band E-plane waveguide filter employing a conventional fin-line filter structure integrated with two E-plane extended notch cavities is proposed. Taking advantage of the double-mode resonant characteristics of the cavity resonators, the presented filter achieves good sharp-rejection without disturbing the passband performance, and the suppression bandwidth is extended with two separated notch cavities to ensure the desired notch frequencies to be located within the notch band.

A prototype of the filter is designed and tested. Measured results show that the insertion loss is 2.6 dB with about a 1.1% fractional bandwidth at 93.9 GHz, and the suppression achieves 85 dB at 91.7 GHz, which is only 2.2 GHz lower than the center frequency.

References

[1] Jin L, Ruan C L, Chun L Y. Design E-plane bandpass filter based on EM-ANN model [J]. *Journal of Electromagnetic Waves and Applications,* 2006, **20**(8): 1061 - 1069.

[2] Szydlowski L, Lamecki A, Mrozowski M. Coupled-resonator waveguide filter in quadruplet topology with frequency-dependent coupling—a design based on coupling matrix [J]. *IEEE Microwave and Wireless Component Letters,* 2012, **22**(11): 553 - 555.

[3] Politi M, Fossati A. Direct coupled waveguide filters with generalized Chebyshev response by resonating coupling structures [C]//*European Microwave Conference Digest.* Milan, Italy, 2010: 966 - 969.

[4] Szydlowski L, Lamecki A, Mrozowski M. Coupled-resonator filters with frequency-dependent couplings: coupling matrix synthesis [J]. *IEEE Microwave and Wireless Component Letters,* 2012, **22**(6): 312 - 314.

[5] Villarroya R L, Goussetis G, Hong J S, et al. E-plane filter design for space applications with advanced and stringent performance requirement [C]//2008 *ESA Microwave Technology and Techniques Workshop.* Noordwijk, Netherlands, 2008: 1 - 9.

[6] Goussetis G, Budimir D. Novel periodically loaded E-plane filters [J]. *IEEE Microwave and Wireless Components Letters,* 2003, **13**(6): 193 - 195.

[7] Xu Z B, Guo J, Qian C, et al. Broad-band E-plane filters with improved stop-band performance [J]. *IEEE Microwave and Wireless Components Letters,* 2011, **21**(7): 350 - 352.

[8] Konishi Y, Uenakada K. The design of a bandpass filter with inductive strip-planar circuit mounted in waveguide [J]. *IEEE Transactions on Microwave Theory and Techniques,* 1974, **22**(10): 869 - 873.

[9] Denisov G G, Kuzikov S V, Lukovnikov D A. Simple millimeter wave notch filters based on rectangular waveguide extensions [J]. *International Journal of Infra-*

red and Millimeter Waves, 1995, **16**(7): 1231 − 1238.
[10] Bogdashov A A, Denisov G G, Lukovnikov D A, et al. Resonant notch filters based on rectangular waveguide extensions [C]//2002 3*rd International Conference on Microwave and Millimeter Wave Technology*. Beijing, China, 2002: 1029 − 1032.

带有陷波腔的 W 波段高截止特性带通滤波器

陈振华　徐金平

（东南大学毫米波国家重点实验室,南京 210096）

摘要:利用低阶 E 面鳍线滤波器结构,结合高 *Q* 值陷波腔,设计了一款具有高带外截止特性的 W 波段带通滤波器. 在传统 E 面鳍线结构的基础上,使用沿 E 面扩展的腔体增强对通带边缘特定频率的抑制,同时保持滤波器的通带特性及整个滤波器结构的简易可行. 为了扩展陷波频带的带宽,在鳍线滤波器的输入和输出端设计了 2 个相互分离的陷波腔以产生不同的陷波频率. 对所设计的滤波器进行了实物硬件的加工及实验测试,实验结果表明,在 1 GHz 的通带范围内,最小插损为 2. 7 dB,对偏离中心频率 2. 2 GHz 处(即 91. 7 GHz)的抑制达到 85 dB. 实验结果与仿真设计吻合良好.

关键词:W 波段;E 面滤波器;高截止特性;陷波滤波器
中图分类号:TN713. 5