Harmonic Rejection Filters for the Dominant and the Higher Waveguide Modes Based on the Slotted Strips

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Abstract **— The simplest notch-type filters to reject the dominant and higher modes in multimode frequency band are proposed using resonant properties of the iris formed by slotted capacitive strips. Various configurations of the slotted strip iris are considered. The simplest one is a centered capacitive strip in a rectangular waveguide with centered single slot that is able to reject the dominant mode up to the TE30-cutoff. The second one is the double-slot capacitive iris that has the ability to reject at the same frequency both the dominant mode and the TE20-mode as well. The third configuration is based on two double-slot capacitive strips placed close to the upper and the lower walls of the waveguide and provides the rejection of the TE10, TE20 and TM11-modes simultaneously. Configurations based on slotted inductive strips to reject TE01 and TM11 modes are also considered. These notch filters are perfectly matched in the operating single-mode range, can be easily fabricated and implemented.**

I. Introduction

Inductive and capacitive strips are the widespread waveguide elements used as matching or structural components of the microwave circuits, having very weak dependence of their parameters on the frequency. On the other hand a metal iris with resonance slot in a rectangular waveguide has a response of the passband section and presents the classical component of the first microwave filters. Lately, considering rather complicated multi-slot configurations and circuit theory treatment, it was shown [1], [2] that such irises are able to form rejection response as well. Further the simplest two-slot iris having rejection response and new "electromagnetic" treatment of the total reflection phenomenon were proposed in [3]. Here the existence of the total reflection frequency was explained by simultaneous excitation of two natural oscillations of the iris. The latter was considered as a waveguide open resonator loaded on above-cutoff waveguides and consequently having the spectrum of complex-valued form the rejection resonance it is required to have at least a pair of natural-oscillations with close real parts of eigen-frequencies and essentially different Q-factors, determined by the imaginary parts; 2) the number of zeros and poles of the frequency response is determined by the number of the slots with different electromagnetic properties.

Considering narrow capacitive strip with a single resonance slot as the limiting case of a three-slot iris, one can expect a resonant rejection characteristic together with very low insertion loss out of the stop band. These notch and stop-band filters were proposed in [4]. It turned out that "a strip with a slot" (see drawings in Fig. 1 and Fig. 2) has a classical response of rejection section with good symmetry relatively to the central frequency and extremely low loss level out of the stop band within the rest part of the operating range. The subject of this paper is the possibility to use the slotted strips as harmonic filters.

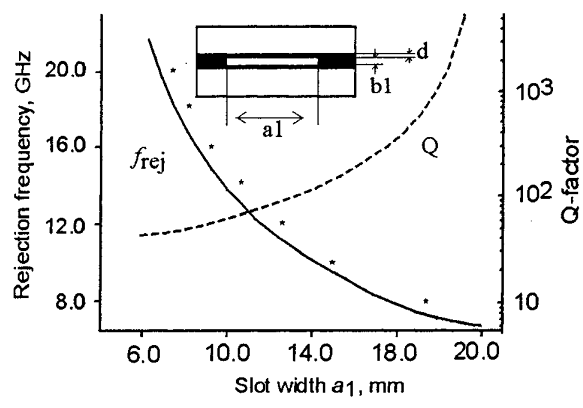

Fig. 1. The dependences of resonance frequency f_{rej} and Q-factor on the slot width for the single-slot strip with $b1 = 1.0$ *mm*, $d = 0.15$ *mm*, t=0.5 *mm* in *WR*90 waveguide.

The mode-matching algorithm and the S-matrix technique were used as the modeling tool for studying the features of the irises formed by the single and double slotted strips as the notch harmonic filters. Such irises were considered as two plane junctions of several internal iris waveguides of smaller cross sections with external rectangular waveguides. As usually the ratio of the mode bases lengths in the smaller waveguides and input/output waveguides was defined by the ratio of their cross-sections or by equivalent asymptotic requirement on the adjacency of cutoffs for higher modes. Experimental data for notch type and band-stop type filters based on the single-slot strips are given in [4].

It is worth to note that only the structures having symmetry both in vertical and horizontal planes are under consideration. The matter is that the lack of symmetry leads to additional mode coupling resulting in worse rejection properties

II. Results and Discussion

A. The single-slot capacitive strip

Dealing with loss-free models of the waveguide elements let us define the resonance iris Q-factor as the ratio of the 3 dB rejection bandwidth to the central frequency of total rejection. The characteristics of the single-slot capacitive strip as a notch type rejection section can be partially inferred from Fig. 1. The frequency of rejection depends mainly on the slot width, which is 2-7% less than the free-space half-lambda (marked by stars) at resonance frequency. The slot height influences somewhat on the rejection frequency as well, e.g., increasing the slot height leads to a small low-frequency shift of resonance. The quality of resonance is determined by the heights of the slot and bonding strips, the smaller the higher *Q*-factor.

A general behavior of the resonance frequency and some additional information about electromagnetic properties of the "strip with slot" are given in Fig. 2 that shows the TE_{10}-mode return loss in a wide frequency band. The set of curves demonstrates a movement of the total reflection frequency as the slot width decreases. Dashed (red in CD-version) curve corresponds to the limiting case when the slot width equals to the waveguide width and the response is typical for the capacitive irises. Even small difference between the waveguide and slot widths (i.e. appearance of narrow vertical strips between two horizontal strips) causes a total reflection resonance placed immediately after cutoff. The reflection of the TE_{10}-mode remains "total" up to the TE_{30} mode cutoff (without taking into account ohmic loss). Though this cutoff is higher than ones of the TE_{20}, TE_{01}, TE_{11}, and TM_{11}-modes, the TE_{30}-mode belongs to the same group of symmetry. Its appearance leads to a power redistribution and, as a result, to reducing the TE_{10}-mode reflection coefficient. Therefore in the case presented in Fig. 2 the single-slot strip is able to suppress efficiently the TE_{10}-mode of the second frequency harmonic. Nevertheless it is possible to extend such an ability up to the third frequency harmonic, reducing the slot height.

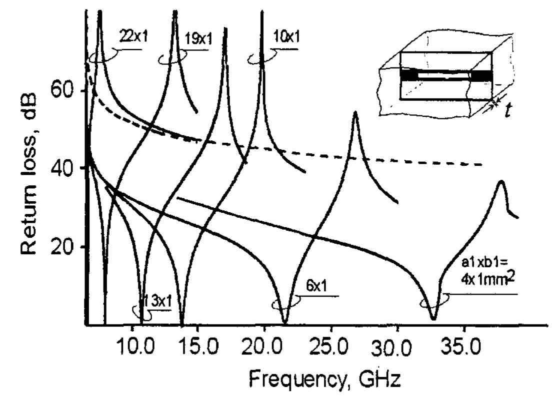

Fig. 2. The modification of return loss response for the single-slot strip in *WR*90 with decreasing the slot width (d=0.15 *mm*, t=0.5 *mm*).

B. The double-slot capacitive strip

Such an object has evidently two types of eigen-oscillations with symmetrical and anti-symmetrical field distributions along axis the OX. It makes possible to reject both the TE_{10} and the TE_{20}-modes. In the case of placement, in the area of the narrow strip, of two slots having the lengths close to half-lambda and excitation by the TE_{10}-mode the resonance of total reflection will appear obviously after the TE_{20}-cutoff (see curves a) and b) in Fig. 3 illustrating insertion and return loss for a narrow double-slot strip). It is very interesting that in this narrow-strip case corresponding curves for the single-slot strip will be identical to each other within several digits. Naturally the field amplitudes in the separate slot of the double-slot iris will be $\sqrt{2}$ times smaller than the amplitude in the slot of a single-slot iris.

The same effect of the electric field strength reduction can be achieved within the single-mode operating range as well. Increasing both the heights of slots we can put the reflection resonance lower than the TE_{20}-cutoff. The response of such a rejection section is presented by the curve c) in Fig. 3. In this wide-strip case, the responses of the single-slot and double-slot strips with equal slots do not coincide (compare curve c) and dashed curve d) for the double-slot and single-slot configurations respectively). If we bring into coincidence resonance frequencies by changing geometry, than the obtained field strength reduction coefficient for the double-strip case would be somewhat less than $\sqrt{2}$.

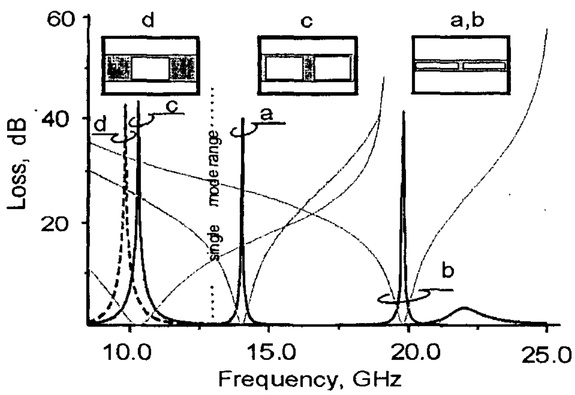

Fig. 3. Insertion and return loss for the single-slot and double-slot strips with t=0.5 mm; d=0.15 mm; $a1 \times b1 = 10.0 \times 1.0$ mm^2 (a), 7.0×1.0 mm^2 (b), 11.35×4.5 mm^2 (c,d) in $WR90$.

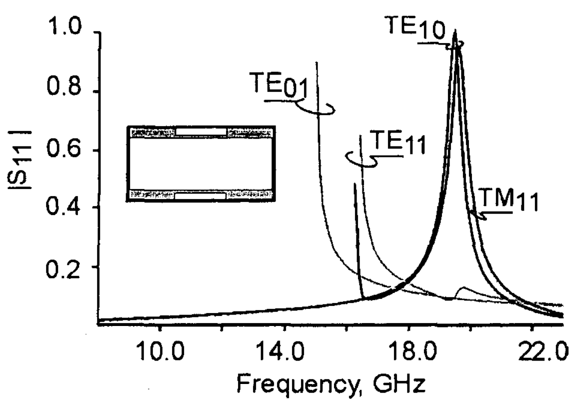

Fig. 4. Reflection coefficients for the dominant and higher modes for a double-slot strip with $a1 \times b1$=7.0×0.5 mm^2, d=0.15 mm, t=0.5 mm in $WR90$.

In general slightly worse quality of the wide slotted strip eigen-oscillations leads to increasing the insertion loss in the desired out-of-stop-band range. For the double-slot configuration additional factor working for the insertion loss increase is the presence of a vertical metal jumper at the waveguide center.

As it turned out the symmetrical and asymmetrical natural oscillations of the double-slot strip are very close in frequency. It provides a possibility to reject both the TE_{10} and TE_{20} modes at a given frequency with very close responses. Fig. 4 illustrates amplitude reflection coefficients for several modes incident on a double-slot strip in rectangular waveguide. As we see both the dominant mode and the first higher one can be efficiently suppressed simultaneously. For the dominant mode the suppression at resonant frequency gets worse starting from the TE_{30}-propagating mode appearance. Note that the TE_{20}-mode can be well suppressed up to 36 GHz (in WR90 case), i.e. within the whole band of the second and third frequency harmonics of the WR90 operating range.

The TE_{01}, TE_{11}, and TM_{11}-mode field distributions belong to the other groups of symmetry than possible natural oscillations of a double-slot strip with the slot lengths close to half-lambda and, consequently, have zero electromagnetic coupling with it. These modes "overlook" double-slot strip as a resonance object. It provides conventional suppression as a metal strip and above-mentioned higher modes have the total reflection frequencies at their cutoffs.

C. The double-side single-slot capacitive strips

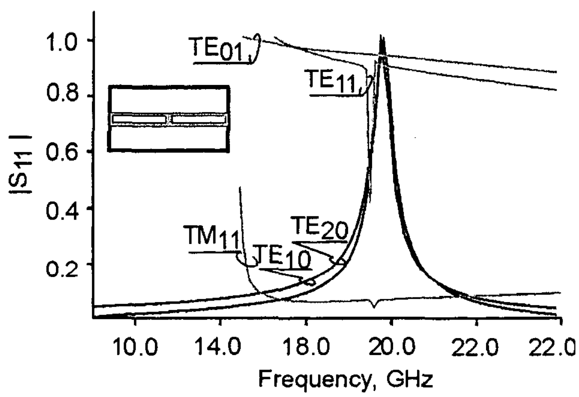

Fig. 5. Reflection coefficients for the dominant and higher modes for a single-slot side-strip with $a1 \times b1$=7.0×0.5 mm^2, d=0.15, t=0.5 mm in $WR90$.

It is apparent that, to suppress the modes with odd indexes along the OY axis we have to use configurations able to support the oscillations asymmetrical in the OY direction. The simplest example presents the double-side single-slot strip shown in Fig. 5. The TE_{01}-mode reacts to this discontinuity even less than in previous cases of the centered strips. In the TE_{11}-mode response only weak spikes mark the presence of resonance slots. However the dominant mode and the TM_{11}-mode have essential coupling with excited natural oscillations that provides a total reflection for each of them. Due to different types of the field symmetry of natural oscillations interacting with the dominant and TM_{11}-modes the frequencies of the total reflection are somewhat shifted. Nevertheless it is possible to reach the 10-20 dB insertion loss for both modes simultaneously at a given frequency.

D. The double-side double-slot capacitive strips

Such a configuration is the wealthiest in properties to be used as a harmonic mode suppressor of resonance type. There is a quadruplet of eigen-oscillations symmetrical and asymmetrical in the OX or OY directions with very close real and imaginary parts of their complex eigen-frequencies. This fact makes possible to reject three modes simultaneously: TE_{10}, TE_{20}, and TE_{11}. The solid curves in Fig. 5 demonstrate good coincidence of the resonance reflection points of these modes. Due to the mode power redistribution the rejection is not total for each of modes, and the amplitudes of the reflection coefficients equal to 0.95 (TE_{10}), 1.00 (TE_{20}), 0.93 (TM_{11}), and 0.09 (TE_{30}). Unfortunately, it was found that in this case the TE_{11}-mode could not be efficiently rejected as well.

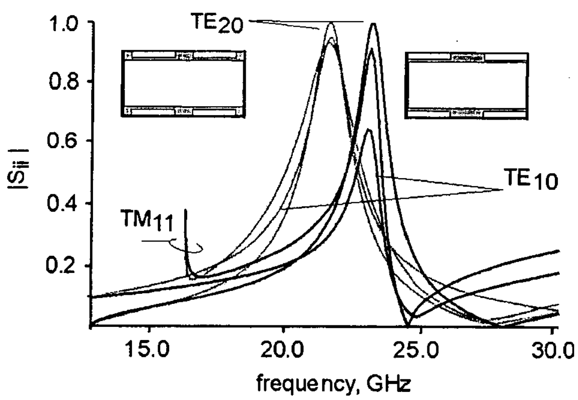

Fig. 6. Reflection coefficients for the dominant and higher modes for double-slot side-strips with $a1 \times b1$=6.0×0.5 mm^2, d=0.15 mm, t=0.5 mm in $WR90$.

For a good coincidence of three resonance curves and to achieve the maximum reflection coefficients it is important to superimpose additional requirement on the iris geometry, namely, the slot placements within the iris "half" (along OX) must be symmetrical as well. The gray curves in Fig. 6 correspond to the geometry that satisfies such a requirement. In the opposite case (black curves, the slots are "pressed" to side walls) the compact bunch of responses breaks up due to the power redistribution, and the maximum values of reflection coefficients are 0.64 (TE_{10}), 0.99 (TE_{20}), 0.91 (TM_{11}), and 0.34 (TE_{30}).

E. The single-slot inductive strips and the slotted strips located round the waveguide periphery

It is clear that the slotted inductive strips are also able to reject the waveguide modes. To provide the minimal loss out of stop band they have to be placed near the narrow walls. It turned out that the single-slot double-side inductive strip rejects TE_{01}, TE_{11} and TM_{11}-modes simultaneously. Resonant curves have good symmetry but the Q-factors of the resonances are in 3-5 times less.

Finally, more complicated structure combined both double-slot double-side capacitive strip and single-slot double-side inductive strip provides simultaneous rejection of all five modes in a narrow vicinity of desired frequency. However the frequency responses for TE_{01} and TE_{11}-modes loose their symmetry

III. Conclusions

The slotted strips are shown to be easily manufactured and implemented tool to suppress undesired signals in single-mode and multimode waveguides. Operating with a number of strips and their internal structure, and with their placement within rectangular waveguide cross-section it is possible to suppress efficiently either separate waveguide mode or the packet of the modes simultaneously, keeping very good matching in the single-mode operating range. The configuration and actual geometry of required one-side or double-side, single-strip or double-strip notch-type rejection filters depends on the frequency and on the field structure of the modes to be rejected. It seems that the complication of geometry of the slotted strip irises and usage of the curved or inclined strips will widen the set of modes, which can be rejected in this manner.

References

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