Evanescent-Mode Bandpass Filters Based on Ridged Waveguide Sections and Inductive Strips

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***Abstract* — A new type of evanescent-mode filters based on ridged waveguide sections is proposed. Insertion of additional inductive strips between ridge sections allows reducing the longitudinal filter size and achieving a sufficient improvement of its stopband characteristics. The features of developed software and results of its application for the filter synthesis and optimization are discussed.**

I. Introduction

Evanescent-mode bandpass filters based on ridged or finned waveguide sections placed in a below-cutoff rectangular waveguide have several advantages over conventional filters based on half-wave resonators due to their compactness, wide stopbands, and increased skirt selectivity. The full-wave models of filters of the discussed type and some results of their design one can find, for example, in [1]-[4].

Improved procedure of initial synthesis, proposed in [4], allowed designing the narrowband and broadband filters with an extended high-frequency stopband. The latter was achieved in [4], in particular, due to a non-conventional choice of below-cutoff filter housing. Usually, it was chosen as one of standard rectangular waveguides, the cross-section of which was smaller than that of an input/output waveguide [1-3].

The main goal of initial synthesis procedure in [4] was to make *Q*-factor of filter resonators, formed by shortened ridged waveguide sections, close to the one of equivalent half-wave resonators. It was done by a corresponding choice of the lengths of notches. However, at some specifications on filter characteristics, these lengths turn out to be so large that the overall filter length becomes comparable with the one for the filters based on half-wave ridge sections. To reduce the filter size and/or extend the high-frequency stopband, the smaller filter housing width has to be chosen. The "charge" for that is an increase, for example, in ohmic loss.

One way of solving the problem of bandstop extension is proposed in the given paper. It consists in an insertion of inductive strips to ridge notches, between ridged waveguide sections. The strips have the same thickness as the ridges so the resulting filter topology presents an all-metal *E*-plane insert symmetrically placed into a below-cutoff rectangular waveguide (see Figs. 1(a-b)). The exact full-wave models are used for obtaining *S*-matrices of all the filter key elements. The analysis of separate parts of filters shown in Figs. 1(c-f), as well as the analysis of filters as a whole, is performed by the generalized *S*-matrix technique.

Numerical results presented below are obtained in the WR 75 waveguide ($a\times b$=19.05×9.525 mm) operating range. Some geometrical parameters are the same for all the considered filters: ridge thickness t=1 mm, height of the filter housing and notches $b_h=b$. The following sum number of the *TE* and *TM* modes was utilized at a filter assembling by the *S*-matrix technique: 10 modes in the ridged waveguide sections, 7 in the notches, and 14 in the strip narrow waveguides. Owing to the symmetry of filter topology relative to the $x=a/2$ plane, only the symmetrical modes were taken into account.

II. Study of Filters' Element Properties

The fact that additional inductive strips can essentially reduce the lengths of below-cutoff notches is obvious. However, the question of how strips influence on the possibility of obtaining the shortened ridged waveguide sections with the desired response is not so obvious and requires an additional study. This question emerges due to the fact that the notches have the character of capacitive load for the ridged waveguide sections and a "parasitic" inductance introduced by strips may upset the phase condition [4] allowing to obtain the shortened ridge sections.

With the single-mode approach, the following formula

$$r \approx \arg S_{11}/\zeta_1 \qquad (1)$$

can be obtained to estimate the length r of ridge resonators shown in Fig. 1(d) or Fig. 1(f). Here, ζ_1 is the propagation constant of the ridged waveguide dominant mode, $\arg S_{11}$ is the phase of this mode reflected from a simple (Fig. 1(c)) or complicated (Fig. 1(e)) reflecting element

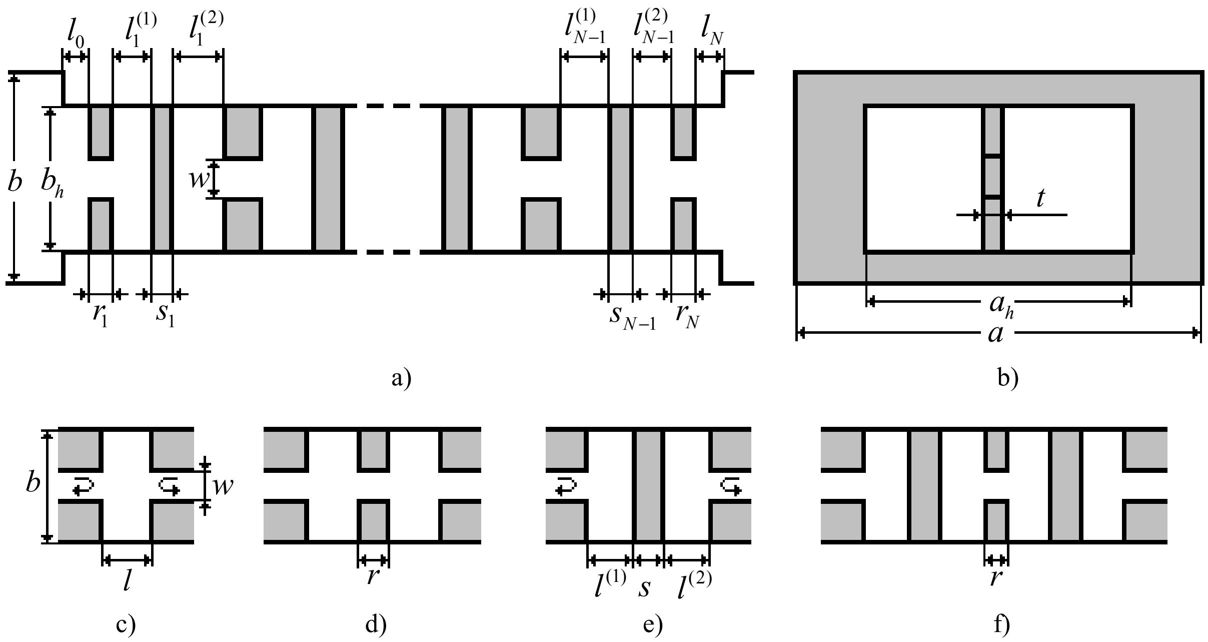

Fig.1. Longitudinal (a) and cross (b) sections of the evanescent-mode filter based on ridged waveguide sections with additional inductive strips; filter elements of conventional (c, d) topology and the ones including inductive strips (e, f).

that provides the required value of the prototype *K*-invertor at the given frequency. It is clear that the shortened resonator may be realized if the value of $\arg S_{11}$ is small and negative (time dependence $\exp(-j\omega t)$ is assumed). The curves in Fig. 2 illustrate how inductive strips affect the value of $\arg S_{11}$. The curve *1* is calculated for the single notch (see Fig. 1(c)) with the length l=11 mm providing the value K=0.042 ($|S_{11}|\approx0.996$) at f=11 GHz in the ridged waveguide having the $a_h\times b_h$ =9.525×9.525 mm cross-section and w=1.7 mm ridge gap.

The same value of $|S_{11}|$ can be obtained in the case of complicated reflecting element shown in Fig. 1(e). The curves *2* ($s = 0.1$ mm, $l^{(1)}=l^{(2)}$=3.12 mm) and *3* (s=0.5 mm, $l^{(1)}=l^{(2)}$=2.6 mm) correspond to such elements. As one can see, even small-length strips affect essentially the value of $\arg S_{11}$ that can lead to increasing the resonator length according to the formula (1) in more than twice.

The influence of the strip length s on the geometrical parameters of resonators formed by complicated reflecting elements (Fig. 1(f)) is demonstrated by curves in Fig. 3:

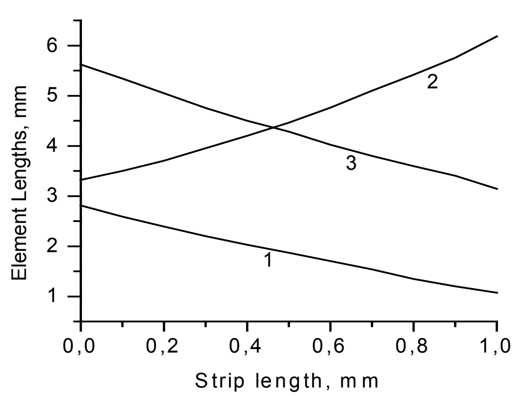

Fig. 2. Phase characteristics of the ridged waveguide dominant mode reflected from simple (curve *1*) and complicated (curves *2*, *3*) elements.

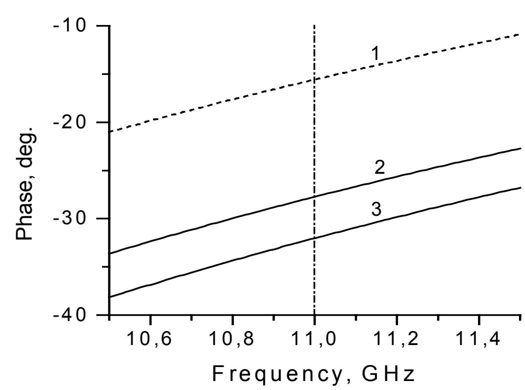

Fig. 3. Lengths of notch (curve *1*), resonator (curve *2*) and complicated *K*-invertor element (curve *3*) depending on the strip length.

1 – $l^{(1)}$; *2* – $r(s)$; *3* – $l(s)=2l^{(1)}+s$. The results are obtained for the notch central-placed strips ($l^{(1)}(s)= l^{(2)}(s)$) and above listed ridged waveguide parameters. Resonators were tuned to the frequency f_{res} ≈10.95 GHz and provided the quality factor Q≈110.

It should be noted that the resonator bounded by simple notches as in Fig. 1(d) has similar properties at l=10.5 mm and r=1.72 mm. One can conclude that the insertion of strips really increases the resonator lengths (curve *2*) at simultaneous reducing the overall length of complicated reflecting element (curve *3*). If varying the strip length s from 0 to 1 mm, the length of the considered resonator structure (two reflecting elements plus resonator section) reduces from 14.6 to 12.5 mm (for the structure with simple elements this length is 22.72 mm). At the first glance, the observed reduction of structure length is a positive factor, however it has a negative factor also. The matter is that the longer resonator is, the lower is the frequency at which this resonator becomes as a half-wave one. It can lead to an appearance of parasitic spikes within the high-frequency stopband and to a reduction of its width. That is why better is to choose the strip size as small as possible on the assumption of requirements on a rigidity of the all-metal insert or features of its making.

III. Features of the Design Procedure

The created numerical design algorithm contains the following stages:

1. Search of ridge gap according to the chosen filter housing and required cutoff frequency of the ridged waveguide dominant mode.
2. Initial synthesis of the filter geometry on the basis of a K-invertor lowpass prototype.
3. Correction of prototype K-invertors and geometry of filter elements that is caused by peculiar properties of small-volume resonators (shortened ridged waveguide sections).
4. Multimode tuning all the resonators to the filter central frequency.
5. 2D interpolation of the multimode S-matrices of filter elements on the given grid of frequencies and one of geometrical parameters.
6. Optimization of filter geometry.
7. Analysis of needed characteristics (insertion and return loss, VSWR, and group delay) of the optimized filter configuration in the desired frequency range.

The main goal of the stage 3 is to make Q-factor of filter small-volume resonators, formed by shortened ridged waveguide sections, close to the one of equivalent half-wave resonators (see [4]).

Stage 4 consists in adjusting each resonator on the required central frequency taking into account the higher mode interaction in the shortened ridged waveguide section. It is necessary to do due to the following two reasons:

– the initial tuning of the resonators to a filter central frequency is performed with the dominant mode only;

– real waveguide elements are frequency dependent and change their own electromagnetic properties within a considered frequency band.

The multimode tuning procedure is described in [5]. Stages 3 and 4 are performed cyclically, until the obtained passband becomes close to the specified one.

The use of the interpolation models on the stage 5 allows reducing essentially the CPU time consumption needed for the optimization of the filter.

The optimization is based on the multi-parametric gradient procedure and carried out at some stages with different goal functions. With the first of them the special emphasis is done on the satisfaction of filter response to the skirt selectivity and width of passband. At other stages, the required level of passband return loss is reached.

The length of strips is one of input parameters and remains invariable during the optimization. At that, the strips are placed symmetrically between two resonator sections ($l_i^{(1)} = l_i^{(2)} = l_i$, i=1,...N-1 in Fig. 1(a)). Only one half of parameters are included in the vector of objective parameters because all the considered filters are symmetrical relative to their center elements.

The corresponding software is realized with Visual C++ tools as Windows (NT, 95, 98) application and is provided by the advanced user interface.

IV. Numerical Results

A great number of numerical experiments were carried out to provide the comparative analysis of conventional and new type of the evanescent-mode bandpass filters. Some of numerical results are shown in Fig. 4 and Fig.5 below.

The insertion loss responses of three five-resonator optimized filters are presented in Fig. 4. All the configurations were designed at the same dimensions of the ridged waveguide as for the curves in Fig. 3 and provide the return loss level not worse than 25 dB within the specified passband 10.5-11.5 GHz. The curve *1* corresponds to the filter based on simple notches. Overall length of this filter is L=54.1 mm. Its high-frequency stopband is limited by the frequency at which the upper-cutoff notch sections (with the lengths from 9.7 to 11.07 mm) are close to the half-wave ones. The curves *2* and *3*

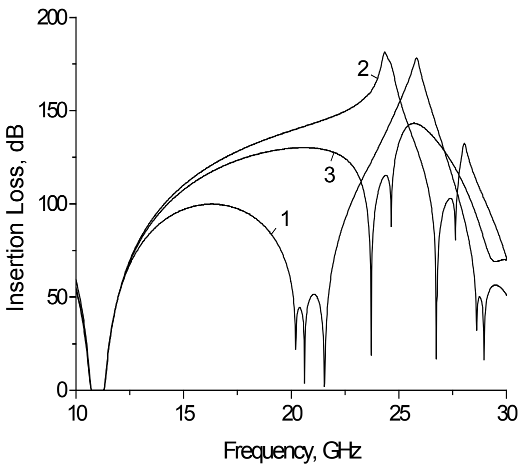

Fig. 4. Insertion loss for the 10.5-11.5 GHz five-resonator bandpass filters. Filters' dimensions (in millimeters): *1* - l_0=l_5= 2.092, l_1=l_4=9.965, l_2=l_3=11.035, r_1=r_5=1.491, r_2=r_4=1.770, r_3= 1.762; *2* – *s*=0.3, l_0=l_5=1.391, l_1=l_4=1.810, l_2=l_3=2.228, r_1=r_5= 2.756, r_2=r_4=4.256, r_3=3.961; *3* - *s*=0.7, l_0=l_5=1.025, l_1=l_4=1.179, l_2=l_3=1.535, r_1=r_5=3.389, r_2=r_4=5.523, r_3=5.118.

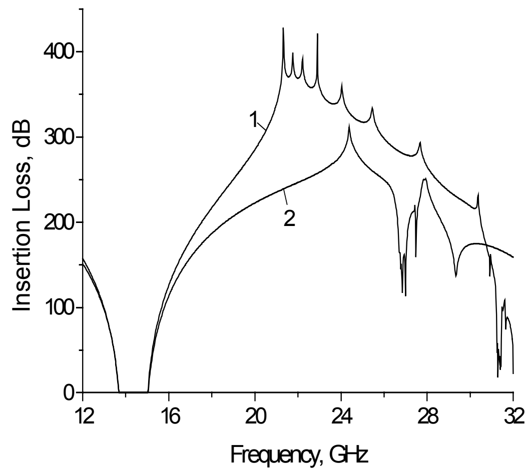

Fig. 5. Insertion loss for the 13.7-15.0 GHz eleven-resonator bandpass filters. Filters' dimensions (in millimeters): *1* – *s*=0.3, l_0=l_{11}=2.200, l_1=l_{10}=1.623, l_2=l_9=2.064, l_3=l_8=2.331, l_4=l_7=2.438, l_5=l_6=2.475, r_1=r_{11}=0.930, r_2=r_{10}=1.881, r_3=r_9=1.521, r_4=r_8= 1.360, r_5=r_7=1.304, r_6=1.290; *2* - l_0=l_{11}=0.551, l_1=l_{10}=6.182, l_2= l_9=7.310, l_3=l_8=7.671, l_4=l_7=7.800, l_5=l_6=7.846, r_1=r_{11}=0.518, r_2=r_{10}=0.791, r_3=r_9=0.757, r_4=r_8=0.749, r_5=r_7=0.747, r_6=0.746.

demonstrate possibilities of the filters based on complicated reflecting elements with the length of strips *s*=0.3 mm (*L*=38.1 mm) and *s*=0.7 mm (*L*=38.6 mm), respectively. The high-quality spikes appear at the lower frequencies for the filters with longer strips (compare curves *2* and *3*). This fact was predicted above on analyzing the curves shown in Fig. 3.

The ridged waveguide with $a_h \times b_h$ =10×9.525 mm, *w*=2.5 mm was used at designing the eleven-resonator filter with the inductive strips of the length *s*=0.3 mm (*L*=66.4 mm). It is illustrated by the curve *1* in Fig. 5. Similar stopband width and high-level suppression can be achieved with the aid of strip-free filter (see the curve *2*) but at the smaller housing cross-section: $a_h \times b_h$ =7.62×9.525 mm. The overall length of such a filter is *L*=82.6 mm.

IV. Conclusion

The above-presented comparative analysis shows that the new bandpass filter configurations have better stopband characteristics than the known analogues. With the correct choice of inductive strip size, the desired result can be reached at substantially smaller longitudinal size and at larger cross-section of the filter housing. The latter fact is very important at designing the millimeter-wave bandpass filters with reduced ohmic loss.

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