Influence of Manufacturing Tolerancies on Central Frequency of a Narrow Band E-Plane Waveguide Filter

Milica Rakić [1], Branka Jokanović[1], Djuradj Budimir[2]

Abstract - **The aim of this work is to master the design of a narrow band waveguide E-plane filter for Ku band that will not need to be adjusted in serial production, therefore its center frequency should be exact. This paper presents the procedure for designing a filter with inserted metal septa and investigates the repeatability of its characteristics with respect to tolerances of both the waveguide housing and the metal septa. It has been shown that longer waveguide's dimension (*a*) has the greatest influence upon filter's central frequency and it has to be precise within limits of 0.1mm. It has also been found that other influences (waveguide's height tolerances *(b)*, unequal dimensions of the halves *(a/2)*, as well as unsymmetrical fitting of waveguide's halves along E-field direction) could be neglected. These findings have been used to obtain the filter that has the center frequency f_c=12.764GHz, which is only 1MHz less then demanded. Measured insertion loss in passband is 0.55dB.**

I. INTRODUCTION

The advantage of waveguide filters over the planar structures is their Q-factor (around 500 at 30GHz), which enables satisfactory filter stopband attenuation. Disadvantage is their volume, which is why the lowest possible filter order is desirable. Such filters have low losses. Low production costs make them additionally suitable for serial production. Slight coupling between resonators even more increases the Q-factor [1], making these filters suitable for narrow, few- percent, bandwidths [2].

Adjustment of filters in serial production is avoided by use of electromagnetic simulators in their precise designing. This is possible with waveguide E-plane filters with inserted metal septa as resonators are made by photolithographic procedure, which is much more precise than mechanical make. Also, the costs of expensive equipment and the time needed for production are reduced.

This paper offers design of input filters for radio link at 13GHz operating at 8Mbit/s, as per ITU-R recommendation F.497-6 [3] (Fig. 1.). Alternative I is applied, according to which for 8Mbit/s capacity links division of first, 28MHz channel into four channels of 7MHz is prescribed. Distance between receiving and transmitting frequency is 266MHz. Lower subrange of first channel is at 12.765GHz and higher is at 13.031GHz. If receiver of a device is operating at lower subrange, then transmitter of the same device is operating at higher subrange, and the other way round. In front of each receiver and transmitter there is a filter, which has to suppress the signal at the other frequency (Fig. 2.). Attenuation of 60dB should be provided between the receiving and the transmitting signal.

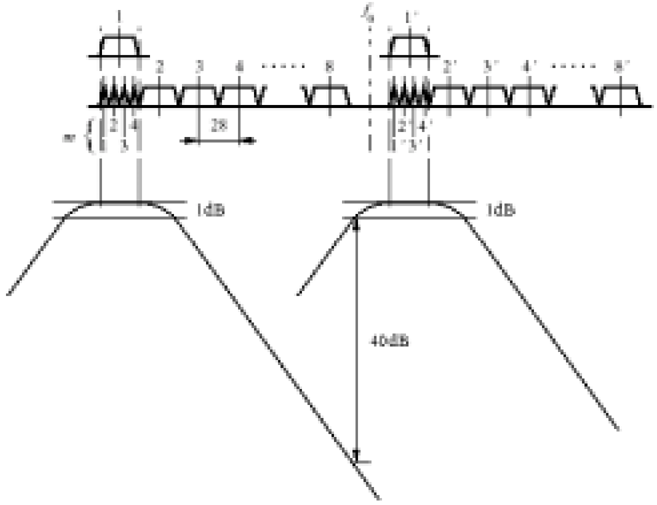

Fig. 1. Radio frequency channel arrangement according to "ITU-R Recommendations F.497-6, *Alternative I*"

However, the input filter need not provide this suppression. Besides the filter, the diplexer shown in Fig. 2 also has the circulator providing attenuation of 20dB between transmitter and receiver. So, requirement for minimal unwanted signal suppression in the filter is decreased to 40dB [4]. The suppression is counted at the frequency at which the filter of opposite subrange has attenuation of 1dB (Fig.1.).

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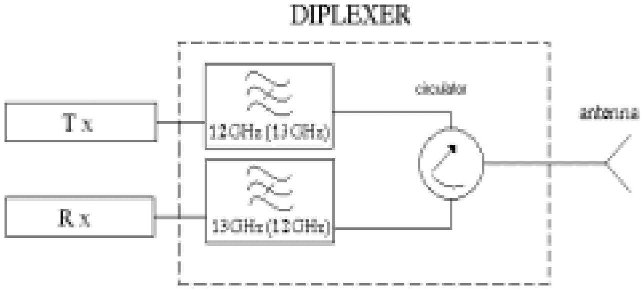

Fig. 2. Diagram of microwave transceiver with a diplexer

In order to reach desired attenuation, it is necessary to design a couple of waveguide filters, one which at $12.75 \div 12.78$GHz passband has attenuation lower than 0.5dB and S_{11} below -15dB, and at 13.017GHz stopband attenuation higher than 40dB, and another with the same characteristics at $13.15 \div 13.45$GHz passband and at 12.78GHz stopband attenuation higher than 40dB.

II. Waveguide E-plane Filters with Metal Septa

A band-pass filter consists of metal septa placed at the maximum of the electric field for mode TE_{10} in E-plane. The septa are metal inductive rectangular diaphragms coupling halfwave resonators (Fig. 3.) [5].

The metal septa may be printed on a dielectric substrate, and, in that case, are considered as infinitely thin. However, in this case, insertion loss of the filter is increased for dielectric loss. For these reasons, our septa consist of an independent metal sheet inserted along waveguide axis. It is necessary that such a sheet should be as thin as possible because its ultimate thickness causes the effect of central frequency moving up [6]. This effect must be taken into consideration upon analysis.

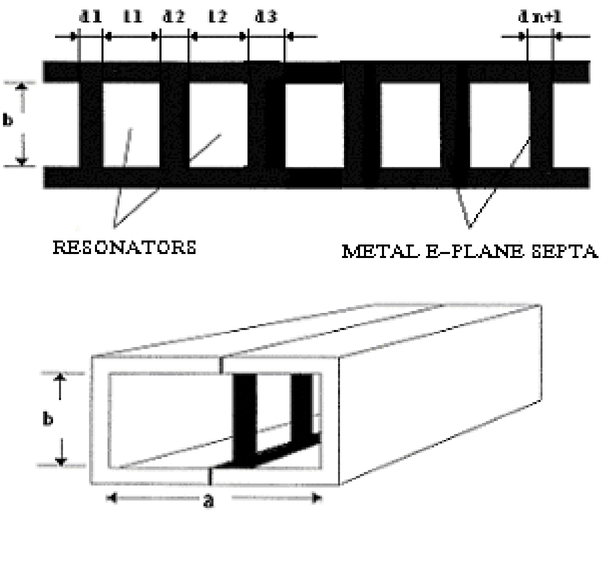

Fig. 3. Structure of E-plane band-pass filter with septa

Standardized equivalent diagram of this filter for dominant TE_{10} mode may be represented by diagram in Fig. 4, where normalized reactances x_{si} and x_{pi} are functions of diaphragm length d_i [7]. Then coupling of higher order modes between adjacent diaphragms is neglected. An impedance inverter represented by symmetrical T-circuit in Fig.5 represents each diaphragm. Sum $(\phi_i + \phi_{i+1})/2$ determines electrical length of the resonator. When the electrical length ϕ_i is chosen so that:

$$\phi_i = -\tan^{-1}(2x_{pi} + x_{si}) - \tan^{-1}(x_{si}) \qquad (1)$$

The normalized ABCD matrix takes the form: $\begin{bmatrix} 0 & jK \\ \dfrac{j}{K} & 0 \end{bmatrix}$,

where:

$$\tan(2\tan^{-1} K) = \frac{2x_{pi}}{1 + 2x_{pi}x_{si} + x_{si}^2}\ . \qquad (2)$$

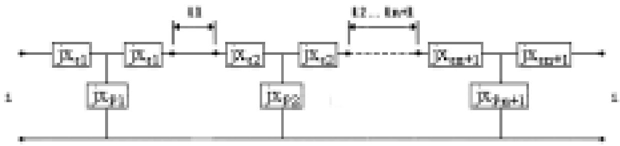

Fig. 4. Normalized dominant mode equivalent circuit

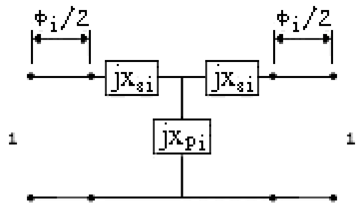

Fig. 5. A symmetrical normalized T-circuit of the metal septum

Such defined K has nonlinear frequency dependence and is not constant. Original procedure of filter synthesis with directly coupled resonators, developed by Rhodes, means linear dependence. Applying before mentioned expressions, resonator length l_i and metal septum length d_i are calculated at central frequency of desired pass-band. Standard Chebyshev's stopband insertion loss level (L_I) is modified by linear discontinuity dependence from frequency and mathematically can be described as follows:

$$L_I = 10\log_{10}\left\{1 + h^2 T_n^2\left[\frac{\alpha\lambda_g}{\lambda_{g0}}\sin\left(\frac{\pi\lambda_{g0}}{\lambda_g}\right)\right]\right\}, \qquad (3)$$

where $T_n(x)$ are Chebyshev's polynomials of the first kind:

$$T_n(x) = \cos(n \cdot \cos^{-1} x)_{0<x\leq 1_1} \quad (4)$$

and

$$T_n(x) = \cosh(n \cdot \cos^{-1} x)_{|x|\geq 1_1}\,. \quad (5)$$

Parameter n is the number of resonators, h defines the passband ripple level, and α determining passband width. λ_{g0} is the guide wavelength at the center frequency, and λ_g is the guide wavelength. Minimum passband return loss is defined as follows:

$$L_R = 10\log_{10}\left\{1+\frac{1}{h^2}\right\}. \quad (6)$$

This approximation method may result in considerably shifted passband in relation to required value and then further optimisation is needed. Correction of passband suggested by Lim, Lee, and Itoh [8] takes into consideration nonlinear frequency dependences of the metal septa impact.

Filter synthesis was performed in EPFIL program package, specially developed for this filter type [9]. This program package uses the method of mode matching, counting impedances of even and odd modes, and thus optimising the filter. Input data are two pass band edge frequencies yielding λ_{gL} and λ_{gH}, passband return loss (L_R), stopband attenuation (L_I), number of modes, waveguide housing dimensions (a,b) and metal-septum thickness (t). The synthesis gives filter order n, length of resonator l_i and length of metal septum d_i.

Filter is synthesized in EPFIL software package using waveguide WR62 housing and 0.08mm thick metal septa for the first channel of lower subrange (Fig. 1.). The synthesis gave a filter of third order, which in passband $12.75 \div 12.78$GHz has insertion loss less than 0.5dB, return loss below –15dB, and in stopband at 12.998GHz attenuation higher than 40dB (Table 1).

TABLE 1. Designed dimensions of resonators and metal septa

i	1	2	3	4
d_i [mm]	3	10.1	10.1	3
l_i [mm]	13.78	13.86	13.78	-

By realization of filter by two-side photolithographic procedure, dimensions were obtained that have certain shift from designed ones, which automatically caused certain frequency shift in filter response.

III. ELECTROMAGNETIC ANALYSIS

As our version of the EPFIL program has limited number (20) of coupling modes, optimization of filter is performed by the method of finite elements in the HP HFSS 5.4 program package.

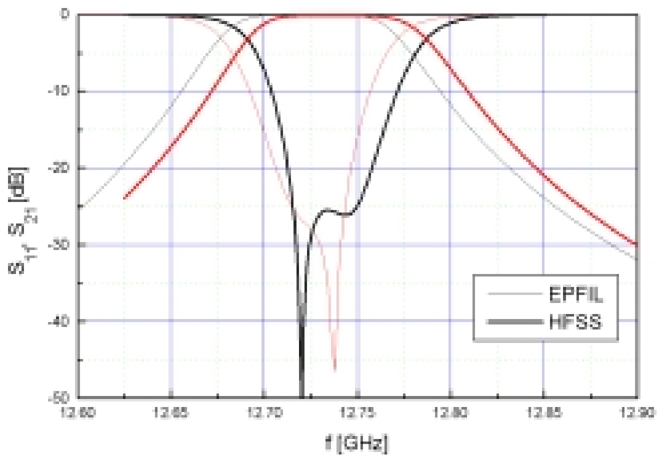

Fig. 6. Result of filter optimization analysed in EPFIL and HFSS program packages

Fig. 6. shows that the filter's central frequency obtained by analysis in HFSS program package is f_c=12739.5MHz, while EPFIL gives center frequency lower for 15MHz. Bandwidths are equal, but there is observable difference in the return loss characteristics.

Program HFSS analysed influence of different dimensions of waveguide housing which are consequence of tolerances in mechanical realization of waveguide to filter characteristics. Fig. 7. shows shift of central frequency upwards in case of waveguide's broader side being shorter for 0.1mm (a=15.7mm) and downwards in case of waveguide's broader side being longer for 0.1 mm (a=15.9mm). The figure shows the central frequency's shift of 53MHz in respect to central frequency of an appropriate housing which is f_c=12739.5GHz.

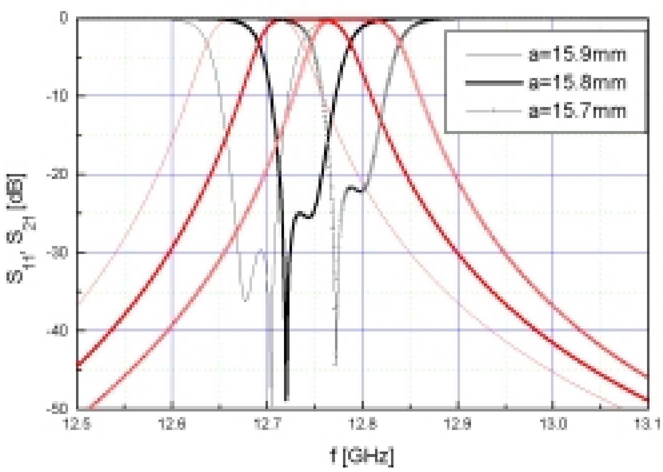

Fig. 7. HFSS simulation of different waveguide housings

By simulation in HP HFSS, it was shown that waveguide's height has no impact on response shift if fabrication tolerances are ±0.2mm. As the housing is made of two halves, unequal realization of the halves has negligible impact as shift of the septum for 0.2mm from the waveguide axis shifts the response for only 4MHz. Unsymmetrical joint of waveguide halves in E-plane also has negligible impact as the 0.2mm step between the two halves gives response shift of 7.5MHz. Finally, the simulation showed that the most sensitive dimension in the housing realization is the waveguide width (*a)* and that this dimension in each half of the waveguide must be realized in tolerance of ±0.05mm.

IV. MEASUREMENT METHOD

To measure S-parameters in such high frequencies, it is necessary to perform calibration of the vector network analyzer. Traditionally, full, two-port calibration methods tipically use three impedance standards and one transmission standard to calibrate network analyzer (VNA). The standards normally used in this method are: shorts, opens, loads and trues (making this what is often referred to as a SOLT calibration).

In case of not having the calibration standards with connectors of the same type as on the measuring instrument, it is necessary to design and characterize new standards. Instead of four SOLT calibration standards, it is easier to make three standards necessary for TRL calibration as suggested by Engen and Hoer in 1979 [10]. This calibration uses true, reflect and line standrads, which are much easier to make in waveguide technique than the SOLT calibration standards.

For the purposes of our measurement, standards have been made to comprise the whole Ku band from 12.4 to 18GHz (Fig. 8.). Reflection standard is made of two short circuits, by which waveguide ports of adapter are closed. *Line 2* is made in appropriate waveguide WR62 for Ku range. Its length is L_2=6.49mm, which represents a quarter of wavelength at geometrical center of the edge frequencies of Ku range.

Fig. 9. shows results of measurement obtained by means of TRL and SOLT calibrations for waveguide filter having low reflection in passband [11]. Considerable differences in S_{11} characteristic are observable. Fig. 9. shows characteristics of designed filter where differences in S_{11} are not so noticeable, because the filter is designed with greater reflection in pass band (S_{11}<-15dB).

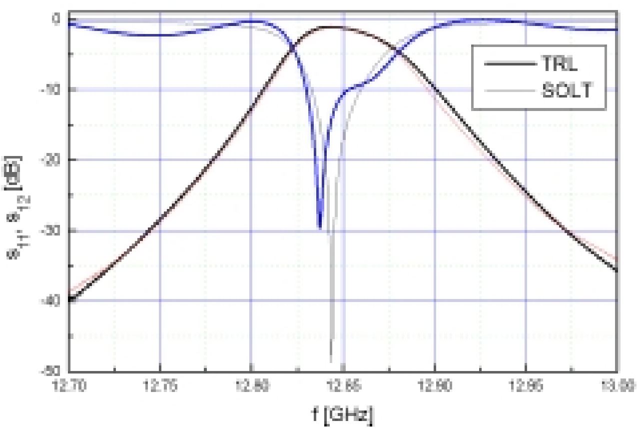

Fig. 8. Comparison of TRL and SOLT calibrations in case of filter with low passband reflection

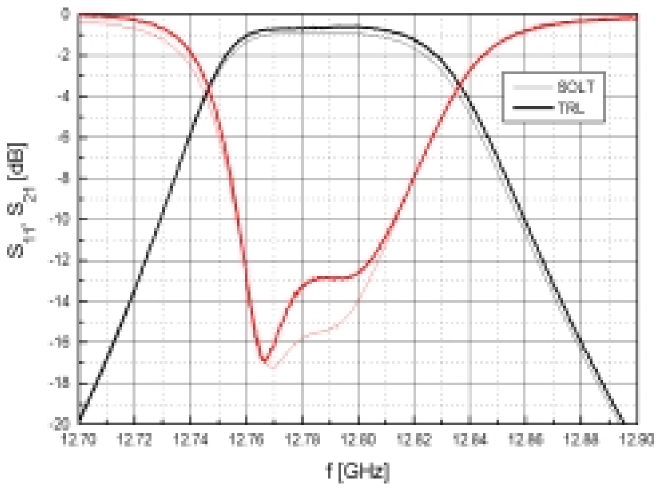

Fig. 9. Comparison of TRL and SOLT calibrations in case of filter with greater passband reflection

V. MEASUREMENT RESULTS

Measurement of realized filter was performed by use of TRL calibration on network analyzer PNA E8634A Agilent Technologies, which has coaxial SMA 2.4mm connectors, and Huber+Suhner, adapters (series 3101) to WR62 waveguide were used. Fig. 10 shows obtained results, along with values obtained by simulation in HFSS and EPFIL. The figure shows that measured filter has passband center frequency f_c=12.733GHz, which is shifted downwards for 6.5MHz in respect to value simulated in HFSS and upwards for 8.5MHz in respect to simulated value in EPFIL. 3dB-bandwidth of the measured filter is 91MHz which is for 4Mz less then simulated bandwidths, and 1dB-bandwidth is 69MHz. Measured insertion loss in passband is 0.45dB.

As HFSS enables obtaining of exact designed central frequency in realization, precise length of resonators was obtained by scaling the resonator’s electrical lengths from measured central frequency to desired one. As the shift is small, scaling is possible in one step. Obtained filter has the center frequency f_c=12.764GHz (Fig. 11). 3dB-bandwidth of the filter is 92MHz, and 1dB-bandwidth is 64MHz, while filter attenuation in stopband at frequencies at which upper subrange filter has attenuation of 1dB (f_{g1dB}=12.998GHz) is 38.5dB, which is very close to required demand. Measured insertion loss in passband is 0.55dB.

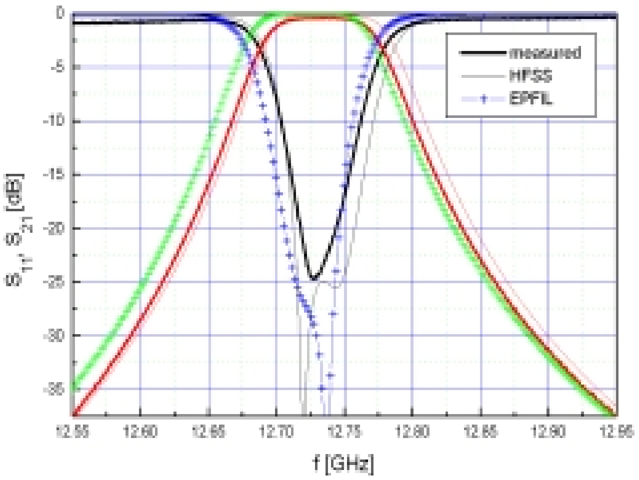

Fig. 10. Measured and simulated results

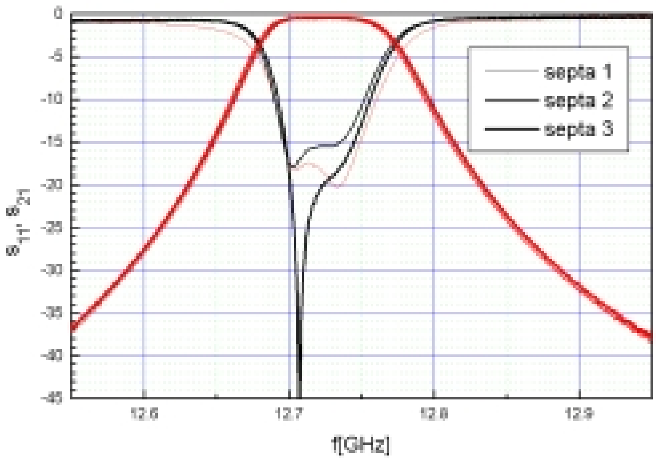

Fig. 11. Repeatability of response depending on metal septum tolerances

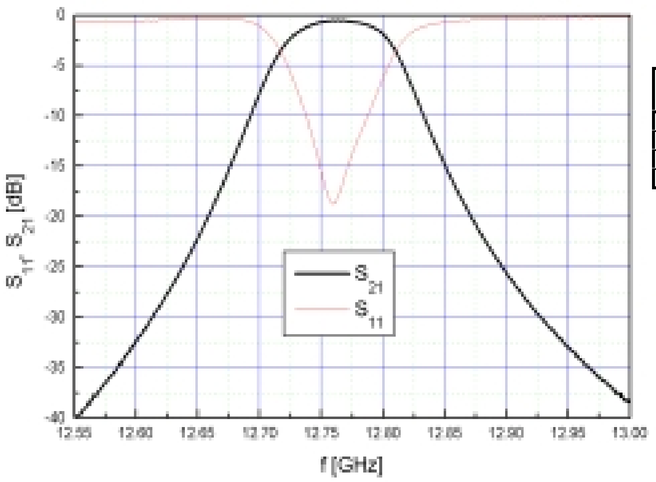

Fig. 11. Measured results of a scaled filter

A. *Tolerances of septa*

Repeatability of characteristics was also obtained in dependence of tolerances of both waveguide housing and metal septa. Repeatability of characteristics in dependence of tolerances of metal septa was investigated on a filter which dimensions are given in Table 1. Fig. 11 shows measured characteristics of the filter in case of tree metal septa, differing one from another only in tolerances of photolithographic procedure. Characteristics were measured in the same housing. As tolerances of two-side photolithographic procedure do not exceed 30µm, all three obtained filters have nearly identical S_{21} parameter for all metal septa. Fabrication tolerances in metal septa make affect only on filtar's *VSWR*.

TABLE 2. Designed and manufactured dimensions of resonators and metal septa

	d_1 [mm]	l_1 [mm]	d_2 [mm]	l_2 [mm]	d_3 [mm]	l_3 [mm]	d_4 [mm]
Projekat	3	13.820	10	13.940	10	13.860	3
Septa 1	3.035	13.815	10.055	13.950	10.040	13.860	3.025
Septa 2	3.025	13.815	10.055	13.950	10.035	13.860	3.020
Septa 3	3.050	13.820	10.055	13.940	10.040	13.855	3.035

B. *Tolerances of housing*

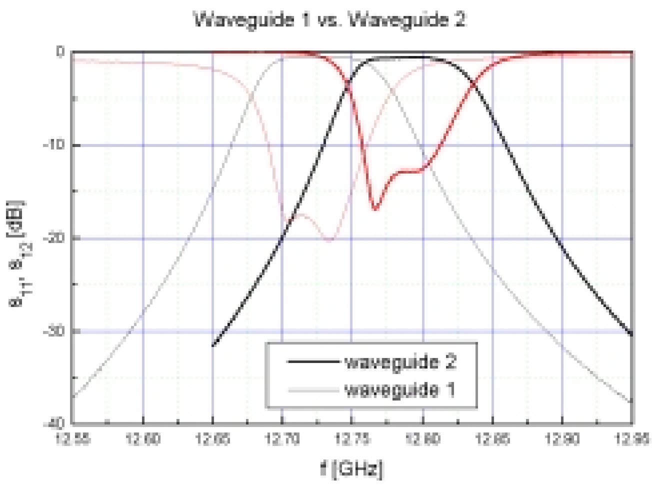

Fig. 12. Repeatability of response depending on housing tolerances

Fig. 12. shows repeatability of response depending on tolerances of the housing. Characteristics of filter with the same metal septum (Septa 1) mounted in two different housings were measured, the housings having the following dimensions: Waveguide 1 (15.6mm X 7.88mm), and Waveguide 2 (15.74mm X 7.85mm). Waveguide 2 is nearer to precise housing, because Chapter 3. showed that tolerances of dimension (*a)* have the greatest influence upon characteristics. Fig. 12. shows that mutual shift between housings is 60MHz,

or 0.5%. This agrees with simulated results in Fig. 7, where shift of 53MHz matches to dimension (*a)* tolerance of 0.1mm.

C. Temperature dilatation

Fig. 13. shows shift of filter's response depending on temperature dilatation. Between room and temperature of –25^{o}C central frequency is shifted for 10MHz, which is tolerable.

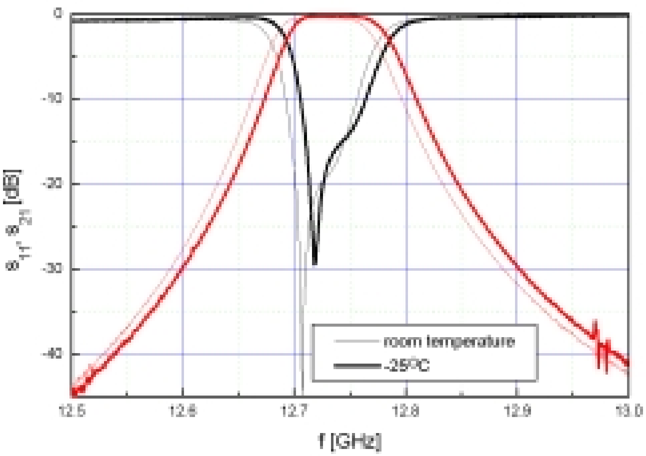

Fig. 13. Repeatability of response depending on temperature dilatation

It has been shown that the most sensitive dimension in terms of realization is the waveguide width *(a)* and that in serial production there is no danger of temperature dilatation. So, it is necessary that the waveguide width is made with precision better than 0.1mm.

VI. Conclusion

It has been shown, both theoretically and experimentally, that waveguide's dimension (*a)* has the greatest influence upon filter's central frequency. In our case of waveguide WR62 it must have less then 0.1mm of tolerance. However, the waveguide being made of two halves, tolerance of each half has to be less than 0.05mm. It has also been found that waveguide's height tolerances *(b)*, unequal dimensions of the halves *(a/2)*, as well as unsymmetrical fitting of waveguide's halves along E-field direction have no influence even when mistakes are of 0.2mm magnitude. These results have been used to realize the filter that has central frequency of f_c=12.764GH, while the aim was to design waveguide filter at precisely determined central frequency (f_c=12.765GHz) with required characteristics in stop-band range, which could be serially produced without any additional adjustment. This goal was achieved. Realized filter has passband insertion loss of 0.55dB, while filter attenuation in stopband at frequency at which filter of upper subrange has attenuation of 1dB (f_{g1dB}=12.998GHz) is 38.5dB, which is very near demanded value (40dB).

Acknowledgement

This paper is a result of projects financed by the Serbian Ministry of Science and Environmental Protection nos. PTR-2002B and IT.1.17.0196.B.

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