Analysis of Frequency Characteristics of a Reflection Symmetric Modal Filter

Evgeniya Chernikova
Television and Control Department
Tomsk State University of Control Systems and Radioelectronics
Tomsk, Russian Federation
chiernikova96@mail.com

Anton Belousov
Television and Control Department
Tomsk State University of Control Systems and Radioelectronics
Tomsk, Russian Federation
ant1lafleur@gmail.com

Talgat Gazizov
Television and Control Department
Tomsk State University of Control Systems and Radioelectronics
Tomsk, Russian Federation
talgat@tu.tusur.ru

***Abstract*—This study investigates a modal filter (MF) based on the reflection symmetrical structure in the frequency domain for the first time. Frequency dependences of $|S_{21}|$ up to 3.5 GHz, are obtained using three different software products with an increase of the separation between conductors from 450 to 2000 µm. We propose the analytical expression for a matched reflection symmetric MF with optimized parameters, which makes it possible to calculate values of resonance frequencies through values of per-unit-length delays without time-consuming calculations of a frequency response. We also performed optimization of the reflection symmetric MF using the criterion of maximizing the bandwidth of a useful signal. It was increased from 0.216 GHz to 0.248 GHz while keeping the first resonance frequency unchanged and maintaining matching.**

Keywords—protective device, reflection symmetry, modal filter, frequency characteristic.

I. Introduction

Currently, radio-electronic equipment (REE) is massively introduced in almost all industries, including military, nuclear and space. As a result, there is a need to protect REE against electromagnetic interference. Signal processing by passive devices has its own application area, including protection against interference signals [1]. Conductive interference, which can be fed and penetrate into the REE directly through the conductors, seems to be especially dangerous [2]. The devices for electronic system protection against natural or man-made electromagnetic interferences with high energies and amplitudes, in particular ultra-wideband (UWB) pulses, based on linear and nonlinear protection elements were presented [3]. Meanwhile to protect REE against ultrashort pulses (USPs) [4], the authors in [5] proposed a technique of modal filtration. This technique is based on modal decomposition of a pulse signal into pulses of smaller amplitude.

MFs have a number of advantages in comparison with the well-known protection devices: high speed, absence of semiconductor components (varistors, zener diodes), high radiation resistance and, as a result, long service life, operation at high voltages, small dimensions, simplicity of design and low cost.

In [6] the author proposed a new approach to improve modal filtration through the reflection symmetric modal filter (MF). The reflection symmetric MF allows you to receive half of the amplitude, in comparison with the MF based on the coupled lines. Meanwhile, in [6] frequency characteristics are examined superficially. The purpose of this work is to carry out a comprehensive research of reflection symmetric MF in the frequency domain.

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II. Research of Frequency Dependence of $|S_{21}|$

To characterize a filter in a frequency domain, *S*-parameters, in particular $|S_{21}|$, representing a transmission coefficient are used. To calculate it, the four-conductor reflection symmetric MF (Fig. 1) was simulated with the harmonic excitation of e.m.f. source of 2 V in the frequency range from 1 MHz to 3.5 GHz with and without taking into account the losses. This frequency range is sufficient for both researching the passband and the first three resonant frequencies. Per-unit-length parameters and response were calculated with quasistatic approach in TALGAT software [7] using schematic diagram of Fig. 2. The resistance values (R) were taken equal to 50 Ohm while the MF length was l=1 m. It was assumed that a T-wave is propagating along the MF. While taking into account the losses in dielectric, we used a widely known model [8] of the frequency dependence of relative permittivity and tangent of the dielectric loss angle of FR-4 material for calculating the per-unit-length entries of the matrix **G**. The per-unit-length entries of the resistance matrix **R** were calculated taking into account the skin effect, the proximity effect and losses in the reference conductor (5 in Fig. 1) by means of the method proposed in [9]. When simulating without losses, entries of matrices **R** and **G** were accepted to be equal to zero.

The MF was simulated with the following parameters: the width of the conductors w=1600 µm, the separations between them s=510 µm, the thickness of conductors t=18 µm, the thickness of the dielectric h=500 µm, the relative permittivity of the environment ε_{r2}=1, the relative permittivity of the dielectric ε_{r1}=4.5 with dielectric loss tangent tgδ=0.017 at the frequency f=1 MHz.

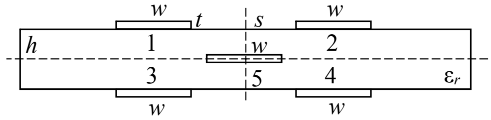


Fig. 1. Cross section of a reflection symmetric MF

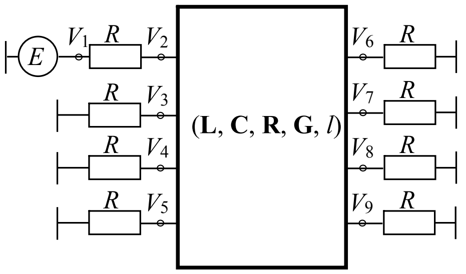


Fig. 2. Schematic diagram of a reflection symmetric MF

To validate the results, the simulation was performed in various software products, using three various approaches: quasistatic, electrodynamic and schematic. In electrodynamic simulation, we used the finite element method. During the simulation which does not take into account the losses, we used the perfect electric conductor (PEC) as the material for the conductors, while dielectric parameters were ε_{r1}=4.5 and tgδ=0. When the losses were taken into account, the conductor material was copper, and dielectric parameters were ε_{r1}=4.5 and tgδ=0.017. Fig. 3 demonstrates the simulation results of $|S_{21}|$ without and with taking into account the losses. Table I presents bandwidths of -3 dB and the values of the first three resonant frequencies (Δf, f_1, f_2, f_3), and Table II – their deviations.

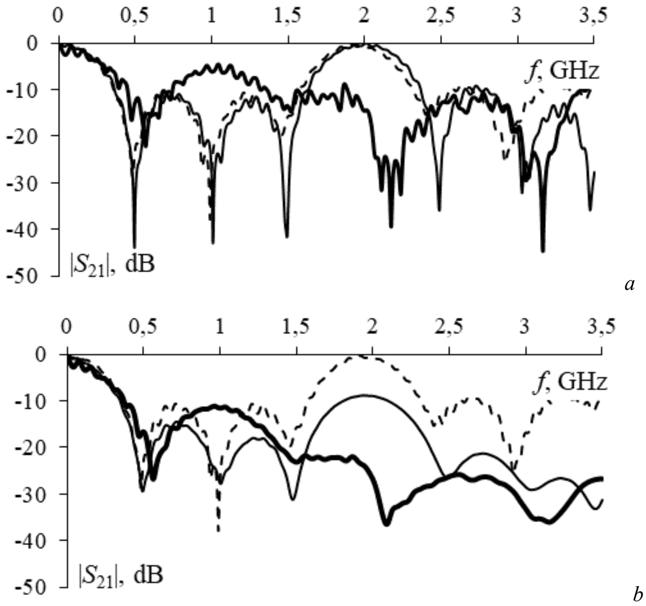


Fig. 3. Frequency dependences of $|S_{21}|$ of reflection symmetric MF for quasistatic (—), electrodynamic (**—**) and schematic (– –) approaches without (*a*) and with (*b*) taking into account the losses.

TABLE I. BANDWIDTHS AND RESONANT FREQUENCIES (GHZ) OF THE REFLECTION SYMMETRIC MF FOR THREE APPROACHES

f	**Quasistatic**		**Electrodynamic**		**Schematic**	
	Lossless	***Lossy***	***Lossless***	***Lossy***	***Lossless***	***Lossy***
Δf	0.216	0.171	0.185	0.164	0.212	0.212
f_1	0.5	0.49	0.567	0.563	0.485	0.485
f_2	1.01	1	1.519	1.683	0.990	0.990
f_3	1.5	1.47	2.11	2.08	1.457	1.457

TABLE II. DEVIATIONS (%) OF THE VALUES FROM TABLE I

f	**Quasistatic and Electrodynamic**		**Quasistatic and Schematic**		**Electrodynamic and Schematic**	
	Lossless	***Lossy***	***Lossless***	***Lossy***	***Lossless***	***Lossy***
Δf	7.7	2.08	0.93	11.62	6.801	12.76
f_1	6.2	6.09	1.52	0.51	7.79	7.44
f_2	20	25.4	1	0.5	21.08	25.92
f_3	16.8	17.1	1.45	0.44	18.306	17.61

Maximum deviation for Δf is 11.62% without taking into account the losses and 12.76% with the losses. For f_1 the consistency in the results of the all approaches, is observed, with the maximum deviation of 7.79% without taking into account the losses and 7.44% with the losses. For f_3 there is a consistency between the quasistatic and schematic approaches with a deviation of 1.45% without taking into account the losses and 0.44% with the losses. From Table I, it can be seen that in electrodynamic approach, the frequency of the second and third resonances is shifted by 0.5 GHz in relation to the frequencies obtained in the simulation by the two other approaches. This is explained by the difference in modeling a dielectric, losses and frequency dependence, as well as by the presence of radiation losses during electrodynamic analysis [8, 10]. In general, we can consider the results obtained with the use of different approaches to be quite consistent. The detailed analysis of the differences and identification of their causes are useful and will be carried out later.

III. ANALYTICAL EXPRESSION FOR CALCULATING THE RESONANCE FREQUENCY

The values of the resonant frequencies in Section II were obtained through simulation of frequency response. To reduce time-consuming calculations, it is possible to obtain the resonance frequencies through the values of the per-unit-length delays of multiconductor transmission line modes.

For coupled lines, the frequency of the first resonance is [11]:

$$f_1 = \frac{1}{2l(\tau_{\text{even}} - \tau_{\text{odd}})}. \qquad (1)$$

For the four-conductor reflection symmetric MF under consideration, the values of per-unit-length delays and their differences are presented in Table III.

TABLE III. VALUES OF PER-UNIT-LENGTH DELAYS AND THEIR DIFFERENCES (NS/M)

τ_1	**τ_2**	**τ_3**	**τ_4**	**$\Delta\tau_1$**	**$\Delta\tau_2$**	**$\Delta\tau_3$**
5.469	5.959	6.474	6.968	0.49	0.49	0.49

Then, for the dependence of the first resonance frequency f_1 on the equalized differences of the per-unit-length delays ($\Delta\tau$) we obtain

$$f_1 = \frac{1}{4l(\Delta\tau)} = \frac{1}{4 \cdot 1\ \text{m} \cdot 0.49\ \text{ns/m}} = 0.5\ \text{GHz}. \qquad (2)$$

This value coincides with the value of f_1 for quasistatic lossless analysis (Table I). Then f_2 and f_3 are equal to 1 GHz and 1.5 GHz, respectively, because of the periodicity arising due to equal time intervals between decomposition pulses (Table III).

It should be noted that previously we carried out the optimization in the time domain by the criterion of equalizing the difference in per-unit-length delays [5], which made it possible to obtain equalized intervals between decomposition pulses. It is the frequency response for the MF with optimized parameters that was simulated, therefore the expression (2) is not universal.

IV. DEPENDENCE OF PARAMETERS ON *S*

To reveal the relationship between time and frequency parameters, we performed a frequency response simulation when s value varies in the range from 450 μm to 2000 μm. The choice of this parameter was due to the fact that a change of s affects the coupling between the conductors: the farther the conductors are from each other, the weaker the edge coupling becomes, but the broad-side coupling becomes stronger.

The values of the time intervals between the decomposition pulses obtained through the per-unit-length delays for l=1 m and the values of resonance frequencies when the value of s varies are presented in Table IV.

TABLE IV. RESULTS OF SIMULATION WHEN CHANGING THE S VALUE

№	s, μm	Δt_1, ns	Δt_2, ns	Δt_3, ns	f_1, GHz	f_2, GHz	f_3, GHz
1	450	0.465	0.537	0.511	0.484	1.01	1.46
2	510	0.49	0.49	0.49	0.5	1.01	1.5
3	550	0.5	0.49	0.48	0.497	1.01	1.52
4	600	0.52	0.48	0.46	0.509	1.01	1.53
5	650	0.546	0.468	0.447	0.517	1.01	1.54
6	700	0.567	0.452	0.429	0.524	1.01	1.6
7	750	0.588	0.437	0.41	0.53	1.02	1.61
8	800	0.61	0.42	0.39	0.534	1.03	1.62
9	900	0.655	0.394	0.348	0.54	1.04	1.769
10	1000	0.7	0.368	0.302	0.55	1.11	1.91
11	1100	0.75	0.34	0.25	0.48	1.12	1.98
12	1200	0.8	0.32	0.2	0.48	1.19	1.925
13	1300	0.85	0.3	0.15	0.483	1.25	1.93
14	1400	0.9	0.28	0.09	0.436	1.26	1.93
15	1500	0.96	0.26	0.03	0.437	1.29	1.95
16	1600	1.01	0.23	0.017	0.437	1.29	1.98
17	1700	1.07	0.16	0.074	0.438	1.29	2.04
18	1800	1.126	0.09	0.13	0.44	1.29	2.06
19	1900	1.179	0.023	0.18	0.44	1.29	2.08
20	2000	1.188	0.04	0.197	0.362	1.27	2.08

It is seen from Table IV that with the increase of s value, the value of $\Delta\tau_1$ increases, however, the value of f_1 varies nonlinearly. The value of f_2 remains approximately constant over the interval of s values from 450 to 900 μm and from 1300 to 2000 μm. In these ranges $\Delta\tau_2$ changes insignificantly, however, starting from s=1900 μm, $\Delta\tau_2$ begins to increase, which leads to a decrease in f_2. The same changes are observed for $\Delta\tau_3$ and f_3.

For clarity, we shall perform simulation of the amplitude-frequency characteristics (AFC) of the MF up to 4 GHz for ten variants of the s values. The resulting graphs are presented in Table VI. It is seen that with the increase of s value, the value of f_1 shifts to the left and the voltage level rises to 0.38 V. The values of f_2 and f_3 shift to the right.

V. BANDWIDTH MAXIMIZATION

One of the most important characteristics of MF is the bandwidth. It determines the maximum value of the frequency range of the useful signal, therefore, its increase will expand the field of optimal application of such MFs. It can be seen from Table IV that the bandwidth decreases from 0.216 GHz to 0.176 GHz, which can lead to a distortion of the transmitted useful signal. Therefore it is necessary to optimize the reflection symmetric MF by the criterion of maximizing the bandwidth while keeping the first resonance frequency unchanged and maintaining matching.

The values of s and w were optimized by a heuristic search in the range of 200–2000 μm with t=18 μm, h=500 μm, ε_{r1}=4.5. As a result, we obtained optimized parameters w=2000 μm, s=1200 μm. A comparison of the frequency characteristics $|S_{21}|$ is presented in Fig. 4. The parameters obtained after optimization allow us to increase the bandwidth at the level of -3 dB from 0.216 GHz to 0.249 GHz.

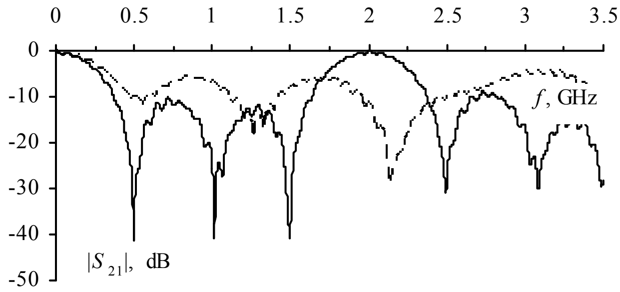


Fig. 4. Frequency dependences $|S_{21}|$ of a reflection symmetric MF before (—) and after (– –) optimization

A comparison of the voltage waveforms at the MF output before and after optimization is presented in Fig. 5, and the values of the amplitudes and the minimum difference in delay of the decomposition pulses are presented in Table V.

TABLE V. COMPARISON OF SIMULATION RESULTS BEFORE AND AFTER OPTIMIZATION

Optimization	U_1, V	U_2, V	U_3, V	U_4, V	Δt_{min}, ns
Before	0.625	0.593	0.616	0.574	0.49
After	0.622	0.582	0.579	0.572	0.21

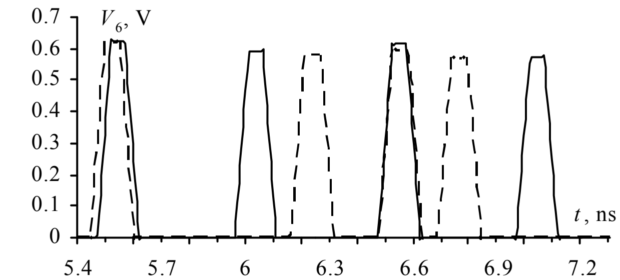
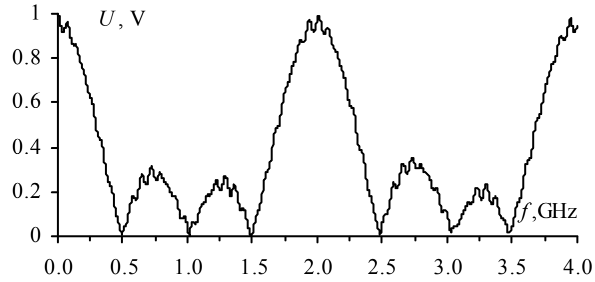
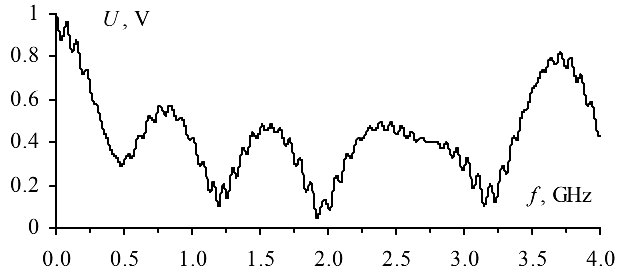
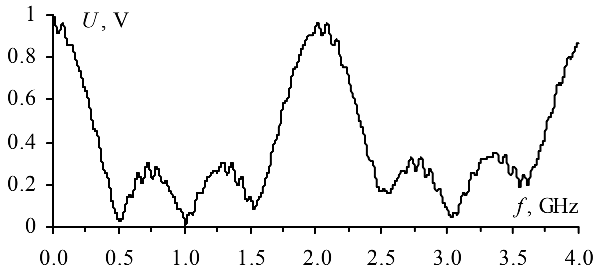
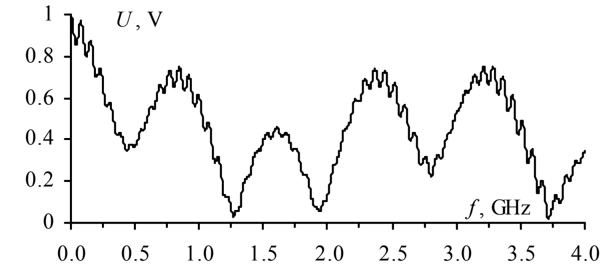
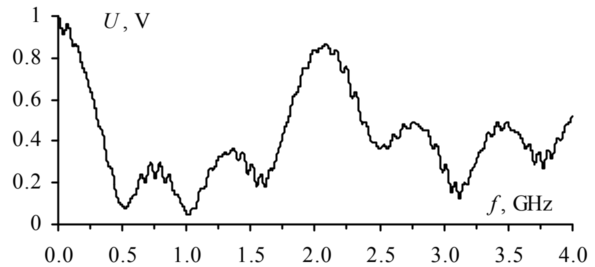
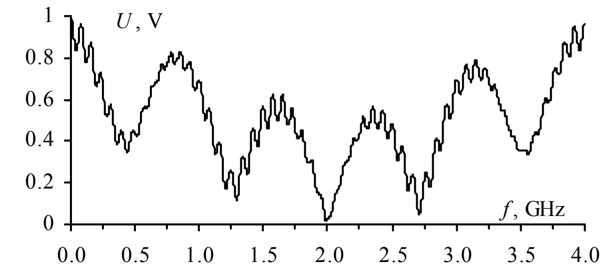
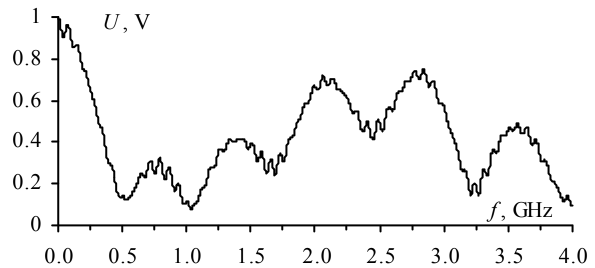
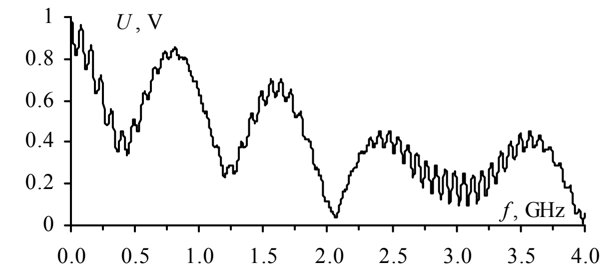
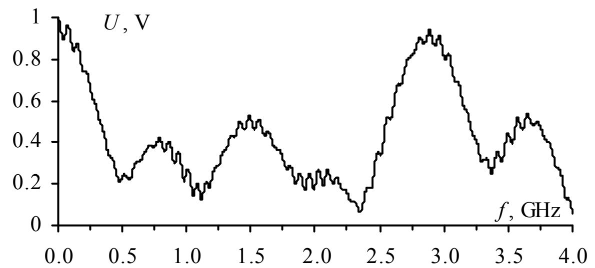
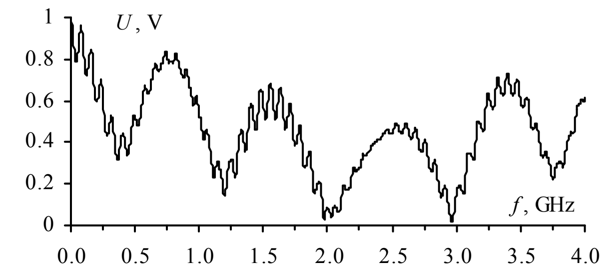


Fig. 5. Voltage waveforms at the MF output before (—) and after (– –) optimization

TABLE VI. AMPLITUDE-FREQUENCY CHARACTERISTICS (AFC) OF MF WITH s=510, 600, …, 2000 µM

s, µm	AFC	*s*, µm	AFC
510		1200	
600		1400	
700		1600	
800		1800	
1000		2000	

From the simulation results, it can be seen that the optimization using the defined criterion has almost no effect on the value of the maximum amplitude of the pulses at the output of the MF (4 times less than the input signal). Meanwhile there is a decrease of the minimum difference in delays of decomposition pulses after optimization, largely caused by the approaching of the fourth pulse to the third one.

Thus, we performed the optimization of the reflection symmetric MF by the criterion of an increase in bandwidth while keeping the first resonance frequency unchanged (f_1=0.5 GHz) and maintaining matching due to the fact that the signal amplitude at the beginning of the line was equal to a half of the exciting e.m.f. source (Fig. 6). Fig. 7 presents the frequency responses at the beginning of the MF before and after optimization. Their comparison showed only a slight deterioration of matching after optimization.

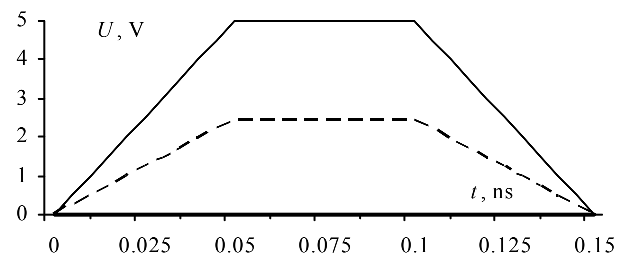


Fig. 6. Exciting e.m.f. (—) and input MF voltage (– –) waveforms

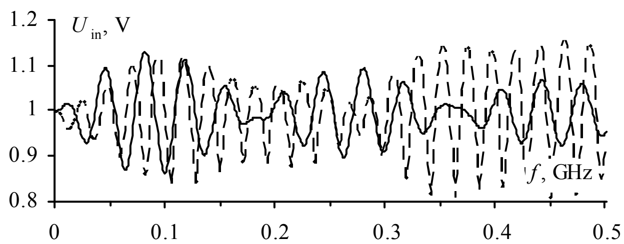


Fig. 7. Frequency dependences of the input voltage of MF excited by harmonic e.m.f. source of 2 V, before (—) and after (– –) optimization

VI. CONCLUSION

Thus, the paper for the first time presents the results of research into a MF based on the reflection symmetric structure in the frequency domain. The authors have made a comparison of the results of a computational experiment using the quasistatic, electrodynamic, and schematic approaches in the frequency range from 10 MHz to 3.5 GHz and proposed an analytical expression for the matched reflection symmetric MF with optimized parameters, which allows calculating the values of the resonant frequencies from the values of the per-unit-length delays of the modes, without calculating the frequency response. In addition, we obtained 10 AFCs with an increase in the separations between the conductors from 450 to 2000 µm. The reflection symmetric MF was optimized by the criterion of maximizing the bandwidth of the useful signal. After optimization, the bandwidth was 0.248 GHz while the first resonance frequency was kept unchanged and the matching was maintained.

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