

A proposal for design of 2 – 4 GHz wideband bandpass filter using suspended substrate stripline for passive radar systems

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ABSTRACT

This article proposes a solution to design of front-end bandpass filters which finds application in wideband receivers for passive radar systems. The structure employs suspended substrate stripline as base transmission lines, dual-frequency resonators, and broad-side coupling patterns to render a wideband, steep cutoff and low-loss bandpass filter that aims at replacing lossy microstrip-based or bulky waveguide-based filters. The structure is able to scale to different operating frequency ranges in electronic warfare systems.

Keywords: Bandpass filters; Wideband; Low loss; Electronic warfare systems.

1. INTRODUCTION

Passive radars have been attractive for both military and civilian air-space surveillance due to their capability of detecting and tracking long-range targets. To this end, the front end of the systems must be able to provide a signal-to-noise ratio (SNR) that produces the required probabilities of detection and false alarm [1]. The input filters, which play a key role in the front end, should meet stringent criteria of loss, bandwidth, and dimensions.

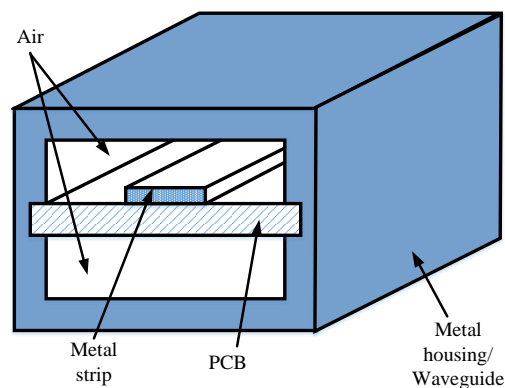
On the other hand, suspended substrate stripline (SSSL) structures have proven as an excellent medium in filter design compared to their counterparts, such as microstrips, striplines, slotlines, and coplanar waveguides, because of their high quality factor and wide range of realizable characteristic impedances [2-5]. Rhodes and Mobbs were arguably the first to design filters and duplexers in various forms [6, 7]. In [8, 9], Belyaev et al. proposed miniaturized bandpass filters with high selectivity based on SSSL. Menzel et al. [10-13] implemented some SSSL filters and duplexers with a quasi-lumped approach, in which resonators were characterized as equivalent LC circuits. The resonators were then arranged in particular order to obtain the synthesized transfer functions. However, the quasi-lumped approach does not take the parasitic factors into account, hence, it limits this method to wideband design.

In this paper, a design of wideband filter based on SSSL is presented. The structure uses dual-frequency resonators printed on one side and broad-side coupling patterns on the other side of the substrate. The designed filter exhibits excellent insertion loss over a wide operating band of 2 – 4 GHz. It is worth mentioning that the structure is scalable, hence, the design procedure can be applied to higher ranges such as 4 – 8 GHz, 8 – 16 GHz.

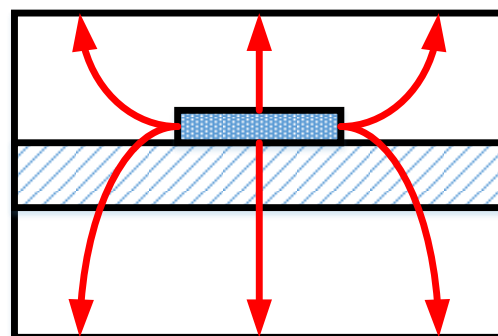
2. DESIGN OF THE WIDEBAND SUSPENDED SUBSTRATE STRIPLINE BANDPASS FILTER

2.1. Suspended substrate stripline transmission line

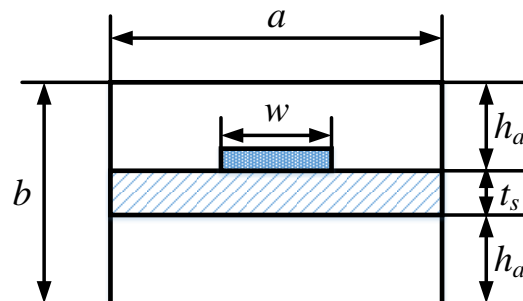
The suspended substrate stripline is a class of transmission line, which consists of a printed metal strip on a thin substrate hanging between two plates of ground plane, hence, the space between the printed circuit board (PCB) and the ground planes fills with air. This configuration allows the SSSL to have a high quality factor, low loss as the electromagnetic waves propagate mainly in the air rather than dielectrics. In practice, the PCB is loaded into a rectangular waveguide, as depicted in Fig. 1a, as a result, small grooves are added to the housing to clamp the substrate. The SSSL structures find themselves in microwave applications from 0.5 GHz to 50 GHz.



(a)



(b)



(c)

Figure 1. (a) Physical implementation of SSSL, (b) quasi-TEM mode propagating along the SSSL, (c) a cross section of SSSL with design parameters.

Fig. 2b shows the ideal cross section of a SSSL transmission line with electromagnetic waves propagating along the SSSL in quasi-TEM mode. Because the metal housing is a rectangular waveguide, which does not normally support the TEM mode, the desired mode must be excited within the cut-off region of the rectangular waveguide host. Hence, the signal frequencies should be well below the cut-off frequency of the waveguide calculated below [14] as the dimensions of the rectangular waveguide are given as length of a and width of b .

$$f_c = \frac{1}{2a\sqrt{\mu\varepsilon}} \quad (1)$$

where μ, ε are permeability and permittivity respectively.

SSSL characteristic impedance (Z_0) is calculated by empirical formulas in [15] as below.

- For narrow strip ($0 < w < a/2$)

$$Z_0 = \frac{\eta_0}{2\pi} \left[V + R \ln\left(\frac{6}{w/b}\right) + \sqrt{1 + \frac{4}{(w/b)^2}} \right] \quad (2)$$

$$\varepsilon_{eff} = \frac{1}{\left[1 + E - F \ln\left(\frac{w}{b}\right) \ln\left(\frac{1}{\sqrt{\varepsilon_r}}\right) \right]^2} \quad (3)$$

$$V = 1.7866 - 0.2035 \frac{h}{b} + 0.4750 \frac{a}{b} \quad (4)$$

$$R = 1.0835 + 0.1007 \frac{h}{b} - 0.09457 \frac{a}{b} \quad (5)$$

$$E = 0.2077 + 1.2177 \frac{h}{b} - 0.08364 \frac{a}{b} \quad (6)$$

$$F = 0.03451 - 0.1031 \frac{h}{b} + 0.01742 \frac{a}{b} \quad (7)$$

- For wide strip ($a/2 < w < a$)

$$Z_0 = \eta_0 \left[V + \frac{R}{\frac{w}{b} + 1.3930 + 0.6670 \ln\left(\frac{w}{b} + 1.444\right)} \right] \quad (8)$$

$$\varepsilon_{eff} = \frac{1}{\left[1 + E - F \ln\left(\frac{w}{b}\right) \ln\left(\frac{1}{\sqrt{\varepsilon_r}}\right) \right]^2} \quad (9)$$

$$V = -0.6301 - 0.07082 \frac{h}{b} + 0.247 \frac{a}{b} \quad (10)$$

$$R = 1.9492 + 0.1553 \frac{h}{b} - 0.5123 \frac{a}{b} \quad (11)$$

$$E = 0.464 + 0.9647 \frac{h}{b} - 0.2063 \frac{a}{b} \tag{12}$$

$$F = -0.1424 + 0.3017 \frac{h}{b} - 0.02411 \frac{a}{b} \tag{13}$$

The calculated values from the above equations should be employed as initial dimensions for further optimization using numerical methods. Eventually, the host waveguide’s cross section has a width of $b = 2.2$ mm and length of $a = 15$ mm, and the cut-off frequency $f_c = 10$ GHz. The 50Ω SSSL transmission line has a width of $w = 3.1$ mm.

2.2. Dual-frequency resonators on suspended substrate stripline

The dual-frequency resonators deployed in the filter are depicted in the Fig. 2 below.

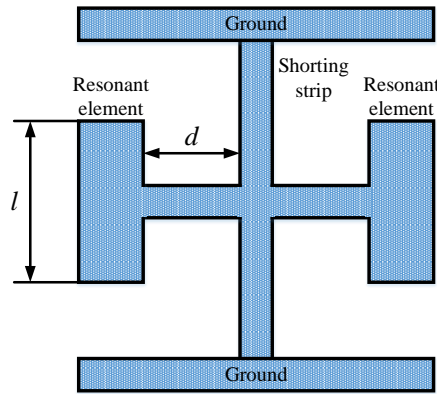


Figure 2. Dual-frequency resonator structure.

The structure comprises two T-shape resonators that are joined together by a shorting strip. The resonant frequencies of each resonator, f_1 and f_2 , can be tuned by modifying the dimensions of l and d on each branch. However, it should be noted that the changes of d also affect the coupling level of the two resonant frequencies.

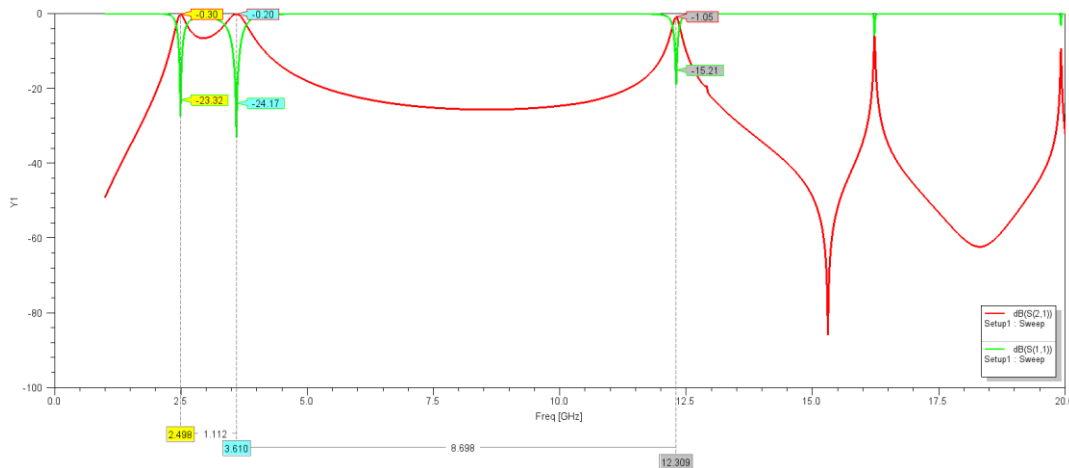


Figure 3. Frequency response of the dual-frequency resonator.

Fig. 3 depicts the frequency response of the dual-frequency resonator. As shown in the figure, the two resonant frequencies are $f_1 = 2.498$ GHz and $f_2 = 3.610$ GHz,

respectively. The distance between the frequencies f_1 and f_2 reflects the coupling level between the two branches of the resonator, and this level is much dependent on d , which is almost half the distance of the two branches. It should be noted that the spurs only appear at high frequencies (more than three times f_2), hence, the filter constructed from such resonators should have a wide stopband, and be able to suppress the second harmonics of the received signals.

2.3. Broad-side coupling patterns

Unlike narrow band bandpass filters, the wideband ones require a higher coupling level between the resonators. As the coupling level provided by edge coupling is insufficient, the broad-side coupling patterns could find them applicable in such structure [16].

The patterns are constructed by etching a rectangular strip on the side of the PCB that is opposite to the one with the resonators, as shown in Fig. 4a, b. From the side view, the patterns overlap the two adjacent resonators, resulting in a higher level of coupling.

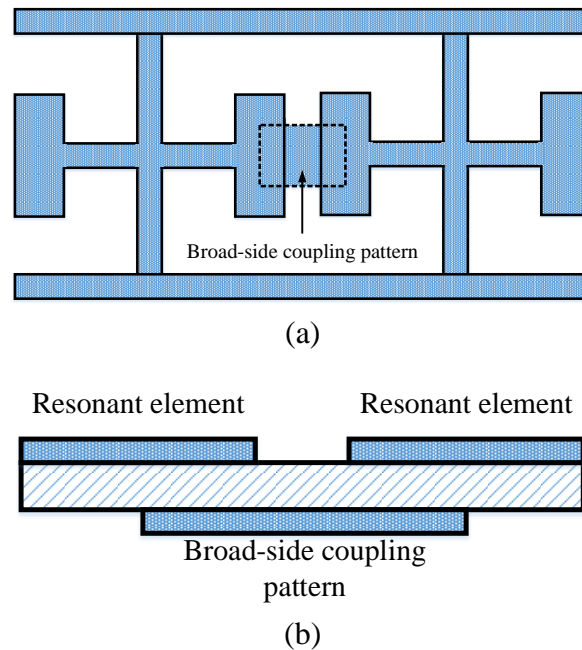


Figure 4. Broad-side coupling pattern from (a) top view, and (b) side view.

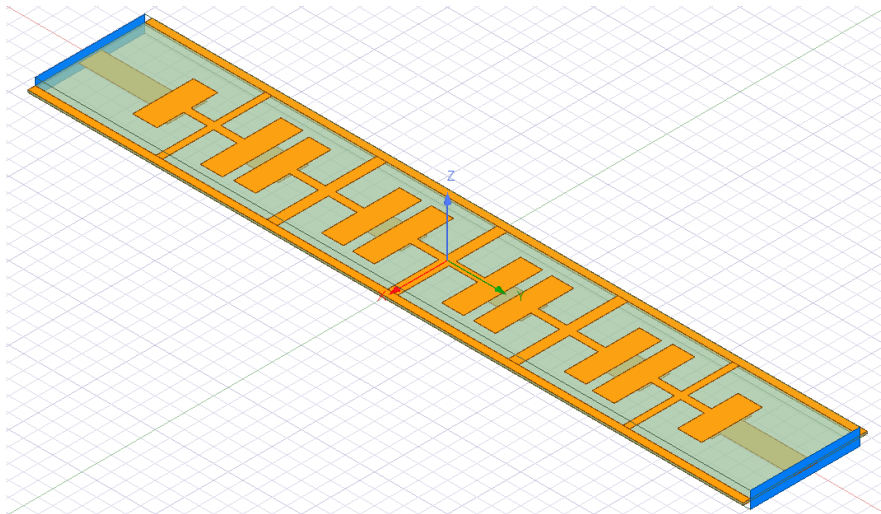
2.4. Design of the wideband bandpass filter

As shown in Fig. 5a, the filter structure, which comprises a PCB and the air boxes inside the host rectangular waveguide, is shown in a perspective view. Fig. 5b depicts the structure with optimized dimensions, but excludes ground patterns at the groves. Five cascading resonators in a row are laid out on one side of the PCB. On the other side, the two 50Ω transmission lines are placed at two ends of the PCBs, while six broad-side coupling patterns are etched between them.

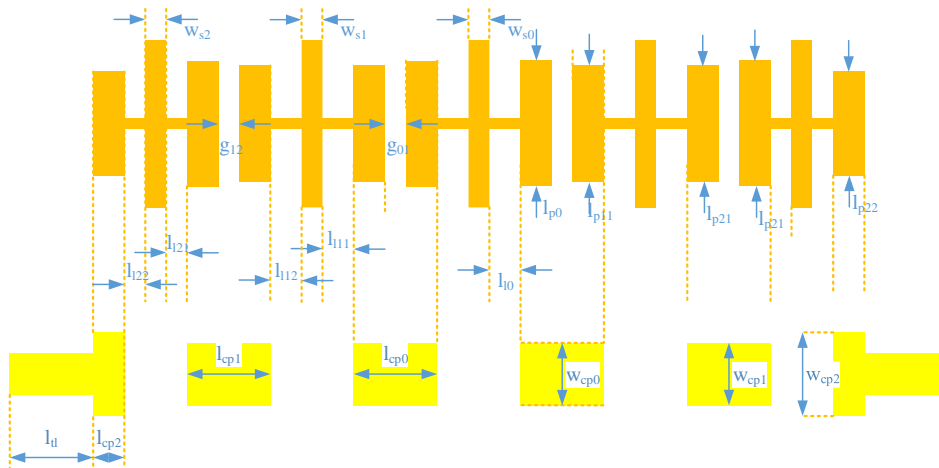
Table 1. The optimized dimensions of the filter.

$l_{cp0} = 7.3 \text{ mm}$	$w_{cp0} = 3.6 \text{ mm}$	$g_{01} = 1.3 \text{ mm}$
$l_{cp1} = 7.2 \text{ mm}$	$w_{cp1} = 4.1 \text{ mm}$	$g_{12} = 1.2 \text{ mm}$

$l_{cp2} = 3.3 \text{ mm}$	$w_{cp2} = 5.4 \text{ mm}$	
$l_0 = 3.9 \text{ mm}$	$w_{s0} = 1.4 \text{ mm}$	
$l_{111} = l_{112} = 3.9 \text{ mm}$	$w_{s1} = 1.4 \text{ mm}$	
$l_{121} = l_{122} = 3.2 \text{ mm}$	$w_{s2} = 0.9 \text{ mm}$	
$l_{p0} = 10.8 \text{ mm}$		
$l_{p11} = 10.7 \text{ mm}$		
$l_{p12} = 10.3 \text{ mm}$		
$l_{p21} = 11 \text{ mm}$		
$l_{p22} = 8.3 \text{ mm}$		



(a)



(b)

Figure 5. The structure from (a) perspective view, (b) top layer (darker shade) and bottom layer (lighter shade) of the PCB.



Figure 6. The schematic of the filter.

The designed filter is schematically equivalent to a filter with ten resonant elements placed inline, and each coupled to the nearest elements, as shown in Fig. 6. The elements of S and L represent two pieces of 50 Ω transmission lines at the terminals. Hence, the designed filter is said to be a 10th order bandpass filter.

The design procedure begins with the synthesis of a coupling matrix for the filter [17]. Table 2 summarizes the values of the matrix entries.

Table 2. Filter’s coupling matrix entries.

$M_{1,1} = 0$	$M_{S,1} = M_{1,S} = 0.98542$	$M_{1,2} = M_{2,1} = 0.813056$
$M_{2,2} = 0$	$M_{L,1} = M_{1,L} = 0.98542$	$M_{2,3} = M_{3,2} = 0.5839$
$M_{3,3} = 0$		$M_{3,4} = M_{4,3} = 0.544367$
$M_{4,4} = 0$		$M_{4,5} = M_{5,4} = 0.53214$
$M_{5,5} = 0$		$M_{5,6} = M_{6,5} = 0.52908$
$M_{6,6} = 0$		$M_{6,7} = M_{7,6} = 0.53214$
$M_{7,7} = 0$		$M_{7,8} = M_{8,7} = 0.544367$
$M_{8,8} = 0$		$M_{8,9} = M_{9,8} = 0.5839$
$M_{9,9} = 0$		$M_{9,10} = M_{10,9} = 0.813056$
$M_{10,10} = 0$		

Each resonator is chosen to have an eigenfrequency of 2.828 GHz in between the two resonant frequencies. Similarly, the coupling pattern dimensions are selected to have a coupling bandwidth of 1.5 GHz. The initial design is simulated to obtain its extracted coupling matrix and eigenvalues. The difference between the extracted values and synthesized values determines the modification of the dimensions of the resonators and the coupling patterns.

3. RESULTS AND DISCUSSIONS

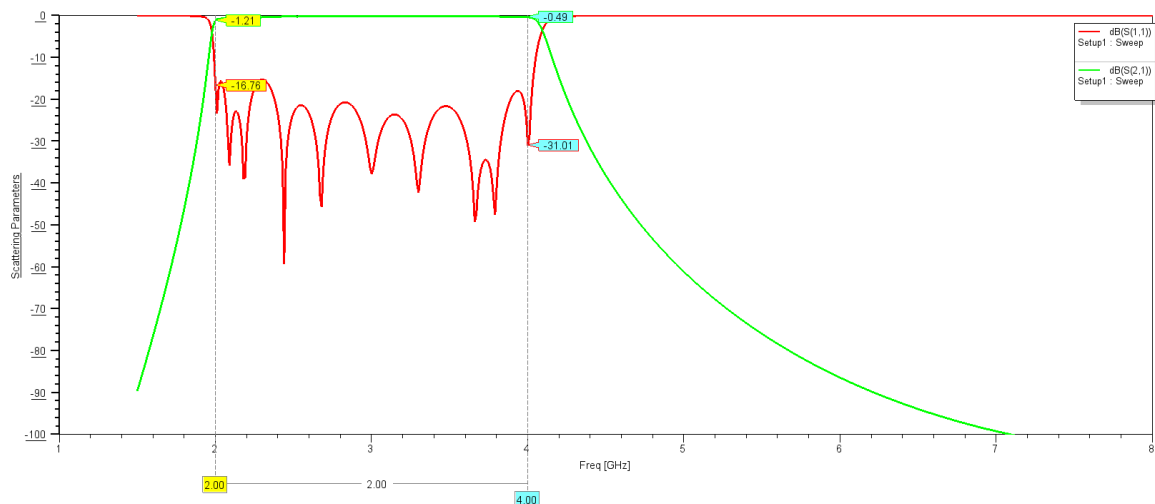


Figure 7. The filter’s return loss S_{11} in red and insertion loss S_{21} in green.

Fig. 7 shows the scattering parameters of the designed filter. Over the range of 2 – 4 GHz, the filter enjoys a return loss of better than 15 dB, which reflects a great impedance

matching of the filter to 50Ω . Meanwhile, the insertion loss of the filter is also better than 1.24 dB in the operating range. This is resulted from the fact that the SSSL based filter does not suffer from radiation loss compared to open structure such as microstrip filters. The structure also obtains wide stopband, showing that it suppresses well second harmonics of the signal.

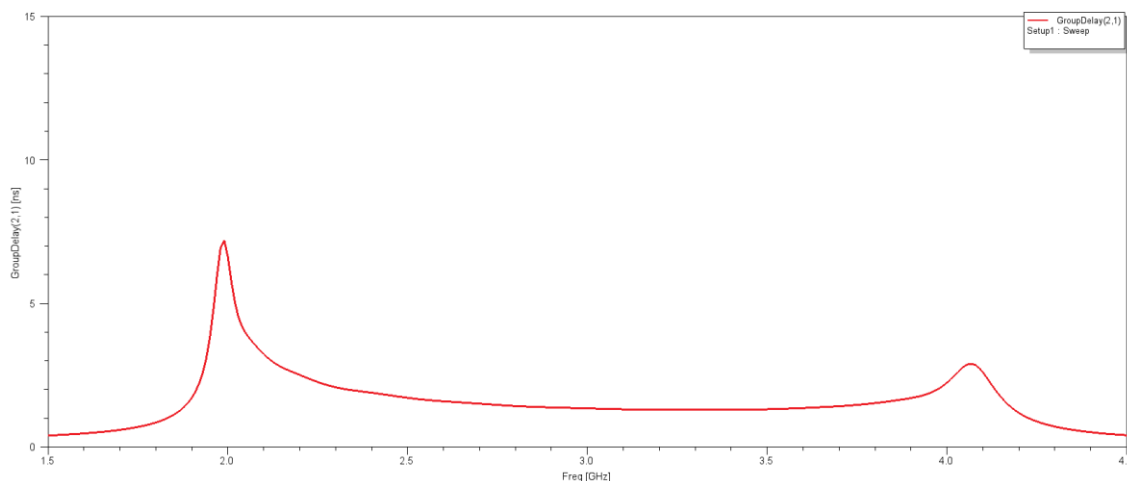


Figure 8. Filter's group delay.

Fig. 8 presents the filter's group delay of 1.3 to 6.6 ns over the passband, showing that the filter has good linearity.

4. CONCLUSIONS

The article proposes a design of 2 – 4 GHz bandpass filter as an input for a wideband receiver due to its compact nature. The filter is able to operate over a wide range of frequencies, up to 66.7% of fractional bandwidth. Moreover, it has low insertion loss over the passband (better than 1.24 dB) as a result of using a suspended substrate stripline transmission line. The design also has a wide stopband showing the ability to suppress the second harmonic of the signals. The filter structure is, furthermore, scalable, hence, applicable for the design of filter at higher bands in the systems.

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TÓM TẮT

Giải pháp thiết kế bộ lọc thông dải băng rộng đầu vào cho dải tần 2 – 4 GHz của tổ hợp ra đa thụ động sử dụng đường truyền mạch dải treo

Bài báo đề xuất giải pháp thiết kế bộ lọc thông dải băng rộng sử dụng cho việc lọc tín hiệu đầu vào từ ăng ten, có thể được áp dụng cho các bộ thu của các hệ thống ra đa. Bộ lọc sử dụng đường truyền mạch dải treo (Suspended Substrate Stripline), cấu trúc cộng hưởng hai tần số, và cấu trúc ghép điện từ hướng ngang cho phép tạo ra các bộ lọc đầu vào băng rộng, tổn hao thấp, độ dốc cao thay thế cho các công nghệ sử dụng mạch vi dải có tổn hao lớn hoặc các cấu trúc ống dẫn sóng có kích thước lớn. Giải pháp minh họa phương án thiết kế cho bộ lọc đầu vào 2 – 4 GHz, và dễ dàng áp dụng cho các dải tần khác trong hệ thống hoặc cho các sản phẩm tác chiến khác.

Từ khóa: Bộ lọc thông dải; Băng rộng; Tổn hao thấp; Hệ thống tác chiến.