A Microstrip Low-Pass Filter Design Using a Modified Radial Resonator in the Application of Aircraft Distance Measurement Equipment

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ABSTRACT

In this paper, the application of microstrip technology is investigated in low-pass filters. A cascade microstrip low-pass filter with a sharp frequency response and a good cut-off bandwidth is presented using a modified radial resonator. The advantages of this proposed filter include minor losses in the transit band as well as the desired return. This filter design shows consistency when compared with the results of simulation and model performance. A comparison between the parameter values of this filter and previous structures indicates that it is desirable. The proposed filter can be used in modern communication systems such as aircraft distance measurement equipment (DME) antenna.

Keywords: Low-pass Filter, Microstrip, Sharpness, Cut-off Bandwidth, Distance Measurement Equipment Antenna

1. INTRODUCTION

Radio waves (RFs) are part of the broad spectrum of electromagnetic waves with specific frequency, phases, and amplitude generated by a transmitting device to carry an electrical signal ranging from 300 MHz to 300 GHz [1]. Consequently, this technology plays an important role in accelerating communication. The higher the wave frequency, the more complex and sensitive the technology will be to its production and reception. One of the problems occurring at high frequency is the interference of radio waves. Frequency interference represents an undesirable overlap of two or more radio frequency signals in a receiver. In a communication system, there are two main ways to reduce frequency interference.

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Due to the increasing development of telecommunication technologies and the need for more receivers and transmitters, it is not appropriate to observe the distance between devices to prevent frequency interference, nor is it economically viable. Frequency allocation provides an alternative strategy for defining different frequency ranges for specific applications. The International Telecommunication Union (ITU) is responsible for analyzing the frequency of devices based on their geographical location. The electromagnetic band gap is a periodic structure used to reject certain frequency bands [2]. In [3], the photonic gap structure (electromagnetic band gap) is used to design a low-pass microstrip filter. One of the most important features of this filter is the optimal level of harmonic attenuation in the cut-off band. However, the main problems with this filter are the lack of frequency response sharpness in the transition zone, inadequate return losses in the cut-off band, significant input losses, large filter size, and its complex structure. Another example of electromagnetic band gap filters is provided in [4]. The bandwidth of this filter is narrow due to the frequency response curve. The main advantages of incomplete ground filters compared to electromagnetic band gap filters are as follows [5]:

1. The dimensions of the filters are relatively small due to the lack of periodic structures.
2. The equivalent circuits of these filters are easily extracted.
3. They are economical.

The disadvantages of this structure include its high radiant radiation and the need to create special boxes [6]. For example, the researcher in [7] uses an incomplete ground technique to design a microstrip low-pass filter with an optical response. One of the advantages of this filter is the sharpness of the frequency response in the transition zone, but in general, it does not have the desired performance, the bandwidth of the filter is narrow, and its recurring losses in the pass band are extremely undesirable. Another example of an incomplete ground structure is given in [8], where open poles are used as the top layer and a Z-shaped resonator as the bottom layer. Due to its frequency response, this filter has the advantage of having optimal return losses in the transit band and relatively wide bandwidth. However, the main disadvantages are its complex structure and very large filter dimensions ($34 \times 34\,\mathrm{mm}^2$). The proposed new structure seeks to address the disadvantages of other structures. This structure is easy to build and has desirable parameters, known as a flat structure. In [9], a step-down microstrip filter is designed using stepwise impedance resonators. This filter consists of two parallel transmission lines Z_1 and Z_2 and an open Z_S. Given the filter structure, by selecting the desired values for the Z_1 and Z_2 transmission lines, the desired cut-off frequency of the filter is achieved, namely 1 GHz according to the application used. This filter has a bandwidth of about 0.13 GHz. It also has relatively good regression losses. The structure of the filter is relatively simple due to the use of step impedances. The reason for adding the Z_S open stopper is to fix the filter bandwidth problem, but as the chart shows, the rate of harmonic attenuation in the cut-off band, even with the addition of the open stopper, provides an undesirable value of about 1.24 GHz. There are several reasons why the filtration factor has been reduced by about 5180.

In [10], a very new structure is used in the design of a microstrip low-pass filter. This filter produces new transmission zeros that sharpen the response of the transit band and increase the bandwidth. One of the most important advantages of this filter is its variable outputs, which can be used in regulated communication systems. According to the filter responses, by changing the voltage size, different cut-off frequencies can be achieved, depending on the type of filter application. However, this type of structure has disadvantages due to its novelty, such as the unavoidable return losses and their non-application at higher frequencies.

The researcher in [11] uses a paired sensory structure to design a microstrip low-pass filter. The filter's bandwidth is 4.5 times that of the cut-off frequency, and it has good sharpness in the pass band, but its large size reduces the quality, which is one of the main weaknesses. Moreover, the return losses in the cut-off band are not desirable. Cone-shaped structures are also commonly used in microstrip filter design [12]. Due to the frequency response curve, cone-shaped structures provide good bandwidth compared to the low cut-off frequency of the proposed filter, but it should be noted that this is due to the larger dimensions of the filter. Furthermore, there are significant return losses in the cut-off bandwidth between 9 and 10 GHz which are not acceptable.

This paper presents a novel microstrip low-pass filter with good performance. The proposed filter applies multiple cascades of modified radial stub resonators with a sharp cut-off frequency response that has a 185 dB/GHz roll-off rate. In addition, U-shaped attenuators provide a wide stop-band of about $14f_c$ with more than -20 dB rejection. The filter has an insertion loss of less than 0.027 dB from dc to 1.31 GHz. The experimental and simulated results are in fair agreement.

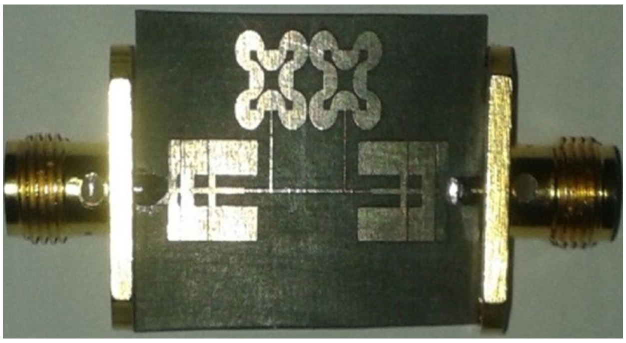


Fig. 1: *View of a microstrip-based low-pass filter structure.*

2. MICROSTRIP TECHNOLOGY

The frequency allocation for each region and system requires radio wave filtering to separate and select different frequencies [1]. Filters are generally divided into the following types: low-pass, high-pass, band-path, and band-stop.

Among the various types mentioned, low-pass filters are important in modern telecommunication systems for eliminating unwanted signals. One of the advantages of using compact elements such as resistors, capacitors, and inductors to design microwave filters is that they provide accurate mathematical relationships to describe these circuits, but due to the use of microwave filters, the specifications of such filters such as efficiency, dimensions, weight, and cost tend to be challenging. Regarding the weight, and cost of compressed elements, it should be noted that the relatively large dimensions of the capacitor and inductor make them unsuitable for use in microwave integrated circuits, and such complexity leads to increased circuit weight. Furthermore, due to leakage losses and additional voltage, there is always the possibility that compressed elements may fail, thus increasing costs and reducing their economic viability.

Studies have shown that metal strips, short-circuited at low frequencies, have an inductive and capacitive property at high frequencies, and can be used as an alternative to capacitors and inductors with the appropriate design. Transmission lines have been developed and implemented using microstrip technology [1]. Fig. 1 presents a three-dimensional view of a microstrip-based low-pass filter.

The microstrip structure contains a conductor strip with width W and thickness t, a sub-electric layer with h thickness and a fixed dielectric r_ε, and a ground plate. Many current applications such as radio communications, modulation, demodulation, filtering, etc., require selective frequency. This frequency selection requires the use of capacitive and inductive effects, so microstrip lines can be used in the filter design, changing the dimensions of the metal strips in the top layer or making changes to the ground layer and dielectric constant. One of the most important advantages of the microstrip structure compared to the compact elements is their variability, enabling the values to be increased or decreased as desired. Other advantages include its simplicity, small size, and cost-effectiveness.

3. DME ANTENNA DESIGN

DME is a navigation aid system whose job is to provide continuous information to determine the distance between the aircraft and the ground station. This distance is measured in miles. It is based on measuring the reciprocating time of radio pulses from the aircraft to the ground station. The sender/receiver of the aircraft emits a combination of pulses with specific characteristics. These pulses are received by the ground station, and after a certain delay, pulses are sent in response. The aircraft receiver receives the pulses and, after deducting the delay time at the ground station, measures the return time of the signal and uses this to calculate the distance to the station. The pilot is displayed or presented to other systems inside the aircraft. Due to its line-of-sight property, the UHF signal of the DME coverage depends on the height and position of the aircraft. This coverage also depends on the specifications of the DME receiver. Operationally, DME coverage should be such that flight plans and routes can be based on it. About 200 to 300 nautical miles is a reasonable DME range. Each DME must be able to respond to 100 aircraft or cover traffic (whichever is the greater). In DME, all aircraft send response pulses at one frequency and receive response pulses at one frequency. Therefore, each aircraft receives the response pulses of all other aircraft along with the squitter pulses and must be able to detect its response and spatial distance to the station according to the time interval of the question and answer. The pulse sent in response to this aircraft is determined by the distance to the station.

Each DME sends query pulses at a random variable rate, while the average frequency of pulse repetition remains constant. In this case, the distance circuit finds the aircraft pulse through a broom search. After sending the question pulse, the aircraft waits a reasonable amount of time to receive the answer, and the next question pulse is sent. Therefore, this waiting period will determine the maximum distance from the DME receiver. For example, if an aircraft receiver needs to detect a distance of 200 miles, a waiting time of $2400\,\mu$s will need to be set after sending the query pulse. Since the ground station sends an average of 3000 pulses per second, after each waiting period of $2400\,\mu$s, the receiver receives about seven pulses. Therefore, the aircraft receiver receives pulses at each interval.

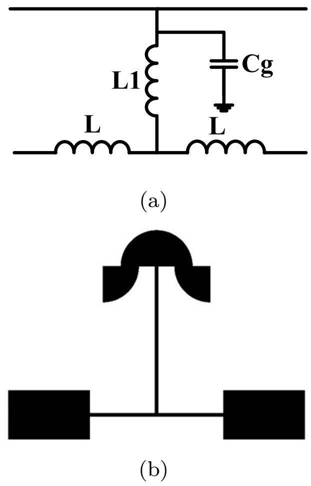


Fig. 2: *(a) LC equivalent circuit for a low-pass elliptical resonator and (b) modified radial microwave structure for a low-pass elliptical resonator.*

These pulses are located at random intervals from the question pulse because they provide answers to the random questions asked by the aircraft. A constant distance is the only response produced to the aircraft at all intervals, equal to the distance to the station. It should be noted that even the fastest aircraft do not exhibit a significant shift in the time taken to send two consecutive pulse questions, so the time interval between sending the question and receiving the answer will necessarily be the same. Since the ground transmitter takes about $100\,\mu$s to recover and answer the next question, no response is generated. There are other random reasons for missing a response. Therefore, radial resonators are one of the most important structures in the use of radio remote sensing systems nowadays due to their relatively good bandwidth compared to other structures. Of course, this type of structure also has disadvantages. In this paper, the researcher aims to modify the radial structure to achieve the desired microstrip low-pass filter with a cut-off frequency of about 1.97 GHz, as used in the previously mentioned bands. It should also be noted that all simulations in this paper are performed using ADS software.

4. CORRECTED RADIAL RESONATOR DESIGN

To achieve the desired cut-off frequency, a low-pass resonator is used with an elliptical response, compressed LC components, and the modified radial microstrip layer provided for it, as shown in Fig. 2. A 50-ohm impedance is also used at the two inlet and outlet ends.

The transmission line parameters for the common elliptical resonator, such as the physical length of the high and low impedance lines, can be obtained from the following equations [12]:

Table 1: *Calculated values of inductors and capacitors for the LC equivalent circuit of the low-pass optical resonator.*

Elements	L	L_1	C_g
Values	1.26 nH	2.78 nH	0.37 pF

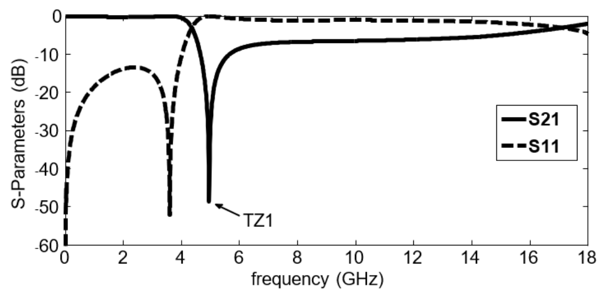


Fig. 3: *Simulated S parameters of the proposed modified radial resonator.*

$$l_{Li} = \frac{\lambda_{gLi}}{2\pi} \sin^{-1}\left(\frac{Z_0 \times g_i}{Z_{0Li}}\right) \tag{1}$$

$$l_{Ci} = \frac{\lambda_{gCi}}{2\pi} \sin^{-1}\left(\frac{Z_{0Ci} \times g_i}{Z_0}\right) \tag{2}$$

where Z_{0Ci} and Z_{0Li} represent the low-impedance and high-impedance transmission lines, respectively. g_i is the effective elements of each elliptical resonator part. λ_{gLi} and λ_{gCi}, respectively, representing the guided wavelengths of the high and low impedance lines.

By obtaining the values of the physical length of the high and low impedance lines, the values of the inductor and capacitor parameters can be obtained using the following equations:

$$L = \frac{Z \sin(\beta l)}{\omega} \tag{3}$$

$$C = \frac{1 - \cos(\beta l)}{\omega Z \sin(\beta l)} \tag{4}$$

where ω is the angular frequency, β is the phase constant, l is the resonator length, and Z is the input and output impedance at $50\,\Omega$. The inductor and capacitor values are listed in Table 1.

Fig. 3 shows the base resonator frequency response diagram. The cut-off frequency is 4.34 GHz and it also has a zero transmission of 4.95 GHz with an attenuation rate of -48.46 dB (TZ1).

As can be seen from the results of the frequency response curve, the value of the cut-off frequency is different from the desired value in this design, so using a combination of curved and slot structures and the LC equivalent circuit, the desired value can be achieved, as shown in Fig. 4 [1].

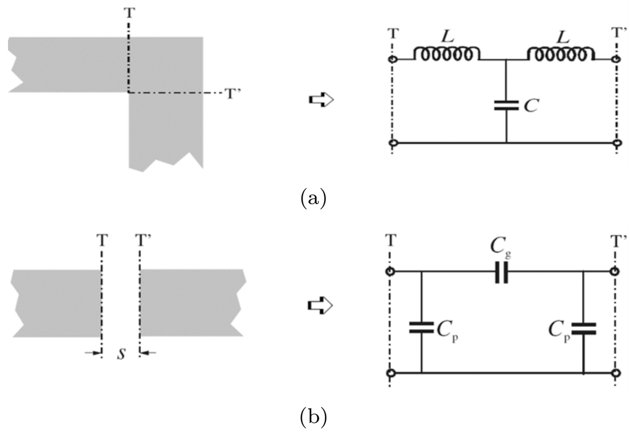


Fig. 4: *(a) Curved structure with its equivalent circuit and (b) gap structure with its equivalent circuit.*

The inductor and capacitor values for the curved structure are calculated from the following equation [1]:

$$\frac{C}{W}\ (\mathrm{pF/m}) = \begin{cases} \dfrac{(14\varepsilon_r + 12.5)\dfrac{W}{h} - (1.83\varepsilon_r - 2.25)}{\sqrt{\dfrac{W}{h}}} + \dfrac{0.02\varepsilon_r}{\dfrac{W}{h}}; & \text{for } \dfrac{W}{h} < 1 \\ (9.5\varepsilon_r + 1.25)\dfrac{W}{h} + 5.2\varepsilon_r + 7; & \text{for } \dfrac{W}{h} \ge 1 \end{cases} \tag{5}$$

$$\frac{L}{h}\ (\mathrm{nH/m}) = 100\left(4\sqrt{\frac{W}{h}} - 4.21\right) \tag{6}$$

Moreover, the capacitor values for the slot structure are obtained from the Eqs. (7) and (9) [1]:

$$C_p = 0.5 C_e \tag{7}$$

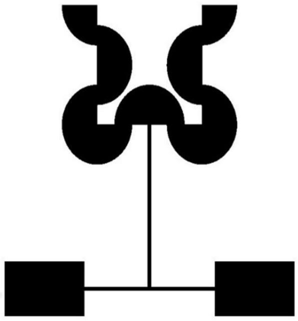
where

$$\frac{C_e}{W}\ (\mathrm{pF/m}) = 12\left(\frac{\varepsilon_r}{9.6}\right)^{0.9}\left(\frac{s}{W}\right)^{m_e}\exp(k_e) \tag{8}$$

$$m_e = \begin{cases} 0.8675 & \text{for } 0.1 \le \dfrac{s}{W} \le 0.3 \\ \dfrac{1.565}{\left(\dfrac{W}{h}\right)^{0.16}} - 1 & \text{for } 0.3 \le \dfrac{s}{W} \le 1 \end{cases}$$

$$k_e = \begin{cases} 2.043\left(\dfrac{W}{h}\right)^{0.12} & \text{for } 0.1 \le \dfrac{s}{W} \le 0.3 \\ 1.97 - \dfrac{0.03}{\dfrac{W}{h}} & \text{for } 0.3 \le \dfrac{s}{W} \le 1 \end{cases}$$

and



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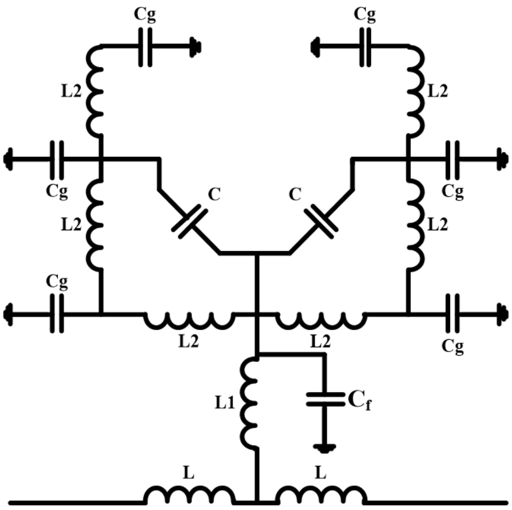

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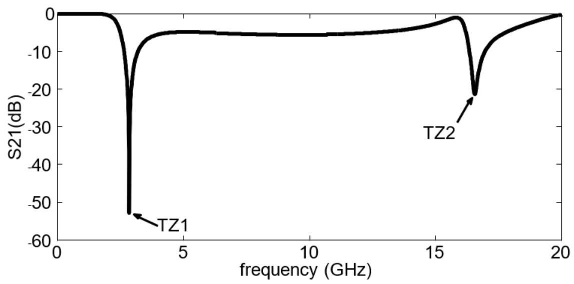


(c)

Fig. 5: *(a) An LC equivalent circuit developed for a low-pass optical resonator, (b) its microstrip structure, and (c) its simulation results.*

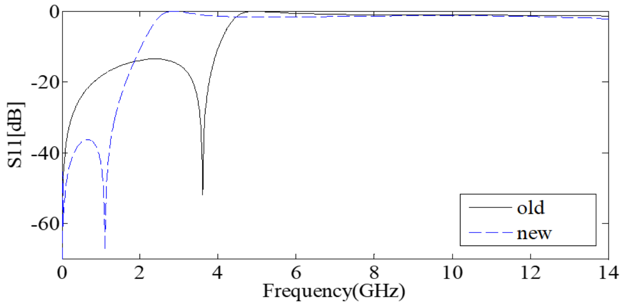
$$C_g = 0.5C_o - 0.25C_e \tag{9}$$

where

$$\frac{C_o}{W}\,(\mathrm{pF/m}) = \left(\frac{\varepsilon_r}{9.6}\right)^{0.8}\left(\frac{s}{W}\right)^{m_o}\exp\left(k_o\right) \tag{10}$$

with m_o and k_o for $0.1 \leq s/W \leq 1$ can be calculated from:

$$m_o = \left(\frac{W}{h}\right)\left[0.619\log\left(\frac{W}{h}\right) - 0.3853\right]$$



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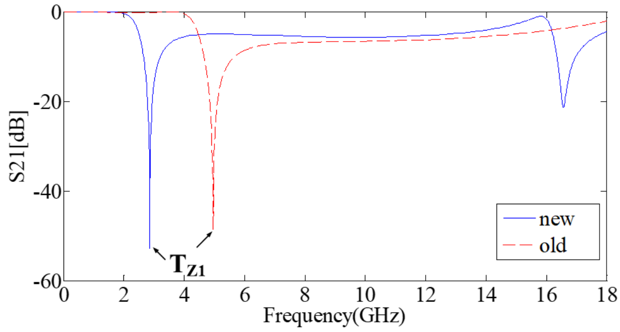


(b)

Fig. 6: *(a) Comparison of the simulated parameter S_{11} developed structure and basic structure, and (b) comparison of the simulated parameter S_{21} developed structure and basic structure.*

$$k_o = 4.26 - 1.453\log\left(\frac{W}{h}\right)$$

By adding the L_2 inductors, according to the curved and slot structures presented in Fig. 5(a), the desired cut-off frequency value can be reached. The addition of L_2 inductors increases the effect of inductors and capacitors on the ground while creating a coupling capacitor between inductors. Fig. 5(b) shows its microstrip structure. According to Fig. 5(c), one of the factors increases the effect of inductors and capacitors or creates coupling capacitors between inductors, leading to zero production in a new transmission at 16.57 GHz with attenuation, thereby producing −21.38 dB (TZ2).

Fig. 6 shows a comparison between the S parameters of the developed structure and the base resonator. It appears that the TZ1 has been moved to 2.67 GHz, reducing the cut-off frequency to 2.22 GHz. Return losses at low frequencies have also improved dramatically.

To better understand the proposed resonator, its LC equivalent circuit is shown in Fig. 7. In this circuit, which has a symmetrical structure, the equivalent of the inductor L is the power supply line with length d_1 and width W. The inductor L_1 is connected to the line with length d and width W, the inductor L_2 is the modified radial stub with radius R, capacitor C is the coupling capacitor between two modified radial stubs, capacitor C_f is related to

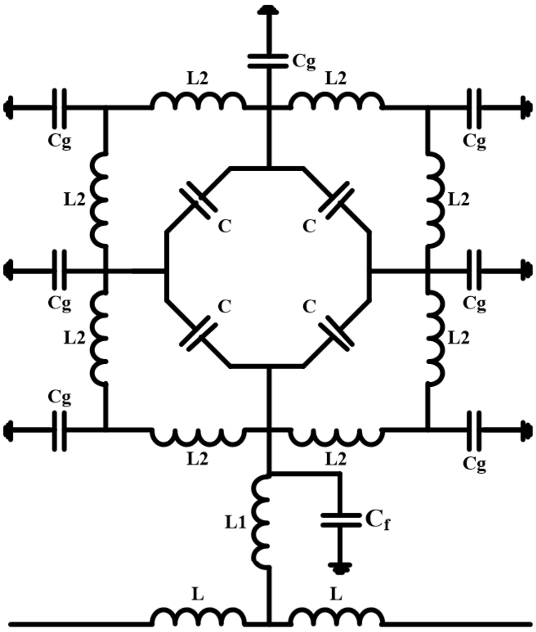


Fig. 7: *LC equivalent circuit of an optimized structure for low-pass elliptical response.*

the sum of the rectified radial stubs results with the supply line, and capacitor C_g is related to the radial stubs corrected by the ground.

In Table 2, the inductance and capacitor values of the equivalent circuit are optimized based on the elliptical response. In Fig. 8, the simulation results of the proposed resonator are compared with the capacitor values listed in Table 2. It can be observed that the two graphs are almost identical.

As can be seen from Table 2, capacitor C has a very small effect on the curve changes, due to the large distance between the two corrected radial stubs.

4.1 U-shaped cascade attenuators

The microstrip low-pass filter is designed by adding U-shaped attenuators to the proposed modified radial cascade resonators, as shown in Fig. 9.

The filter designed by ADS software is simulated and its frequency response curve results presented in Fig. 10. The filter has a cut-off frequency of 1.97 GHz. The bandwidth of the cut-off ranges from 2.13–31 GHz, which at approximately 28.87 GHz is 14 times the cut-off frequency. The bandwidth response is 0.2 GHz, from −3 dB to −40 dB. Recovery losses (RL) range from zero to 0.62 GHz is −23 dB. As can be seen from the curve, the third harmonic of the filter has the highest attenuation. The input losses (IL) of the filter in the transition band from zero to 1.31 GHz are 0.027 dB, while the filter dimensions are 250.3 mm^2. A comparison between the proposed filter in this study and those in previous studies is in Table 3.

Table 2: *Calculated values of inductors and capacitors for the LC equivalent circuit of the optimized radial resonator.*

Elements	L	L_1	L_2	C_g	C_f	C
Values	0.88 nH	1.84 nH	50 fH	0.29 pF	0.25 pF	0.01 pF

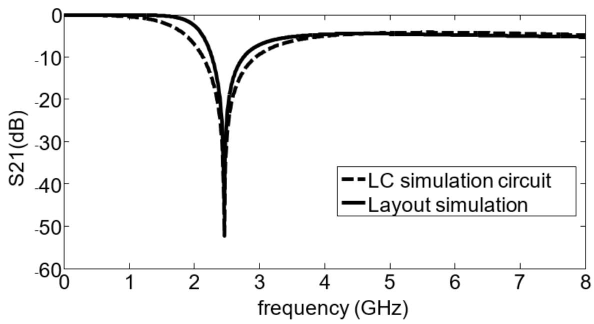


Fig. 8: *Comparison of results for the simulated S parameters of the LC circuit and its microstrip structure.*

5. DME ANTENNA

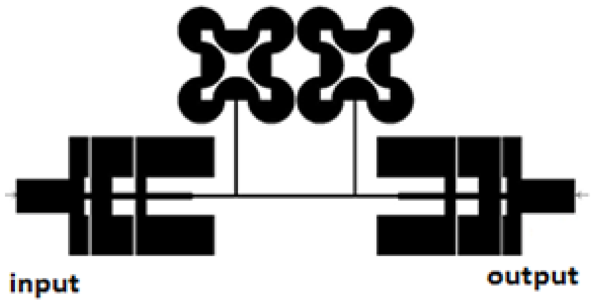
Antennas are the interface between the aircraft and outside world. Aircraft antennas are considered to be radio distance finders. Various antennas on aircraft are used to facilitate communication at different operating frequencies, including the distance meter antenna. In the case of a long-range antenna, the data and measurements on the aircraft must first be transferred to the ground station, then recorded and analyzed. Remote sensing antennas are installed only on prototypes of commercial and combat aircraft and do not appear in all fleets. In the case of the ILS helicopter, they are put in the fleet and the time is re-broadcasted on the ground station. The frequency band used is 1.9–2.5 GHz, while an alternative frequency band of 4.15–4.25 GHz has recently been used for advanced aviation equipment. The first prototype or aircraft produced has a rangefinder antenna with one or two blades installed at the lower level of the aircraft to suit the flight. The rangefinder system can obtain real-time analytical information about many flights. The remote sensing system has many advantages over aircraft flight testing and is not like the old data recording systems that provide real-time data analysis for pilots after the aircraft returns to the remote sensing system. The DME antenna shows the speed and changes needed to improve flight testing at high speeds, as well as the number of landing gear points, generally reducing the cost of flight tests.

The microstrip filter designed in this work has a cut-off frequency of 1.97 GHz, and can be used in the aircraft's DME antenna, depending on its frequency band. The designed filter can be used on the DME antenna due to its desirable specifications such as

Table 3: *A comparison between the proposed filter in this study and those in previous studies.*

	[13]	[12]	[14]	[11]	[15]	This work
f_c (GHz)	3.2	1.04	1.18	0.5	1.76	1.97
Passband						
RL (dB)	18	18	40	16.3	14	23
IL (dB)	1	0.5	N/A	0.5	0.39	0.027
RSB	1.66	0.44	1.32	1.58	1.6	1.76
Roll-off rate (dB/GHz)	5.89	135	36.3	95	94.9	185
Circuit size (Norm.)	0.12×0.063	0.18×0.22	0.079×0.079	0.104×0.214	0.104×0.123	0.191×0.105
Figure of merit (FOM)	2586	5181	11543	13488	27292	32317

RL = return loss; IL = insertion loss; RSB = Relative stopband width; Norm. = Normalized to f_c



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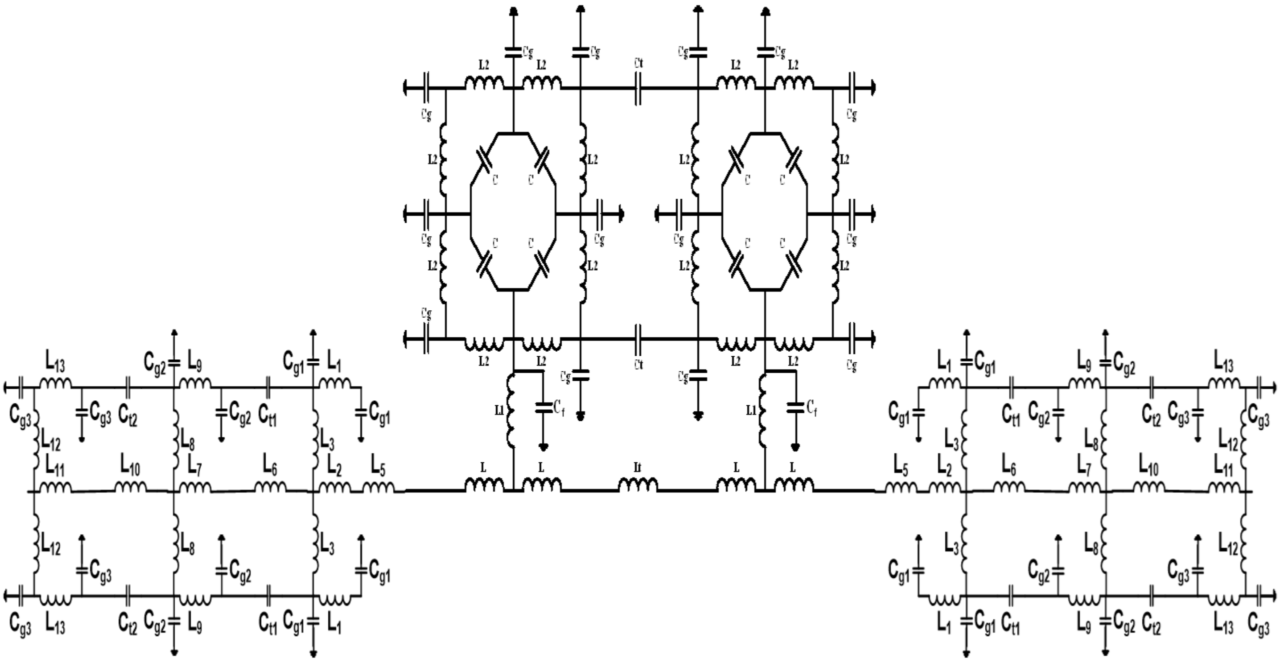

(b)

Fig. 9: *(a) Microstrip structure and (b) LC equivalent circuit of the proposed low-pass filter.*

sharpness of response, optimal bandwidth, and small losses.

6. CONCLUSION

A new low-pass microstrip filter is designed in this study using modified radial resonators and U-shaped attenuators. The design of this filter using inductors and capacitors involves a large number of compact elements, which in addition to their complexity, result in significant losses, but the microstrip structure means the filter has the same efficiency and much smaller dimensions. The cascade structure of the modified radial resonators leads to the sharpness of the optimal filter response, while the cascading U-shaped attenuator structure of this filter with a cut-off frequency of 1.97 GHz, leads to the production of weakening poles, ultimately increasing the cutting

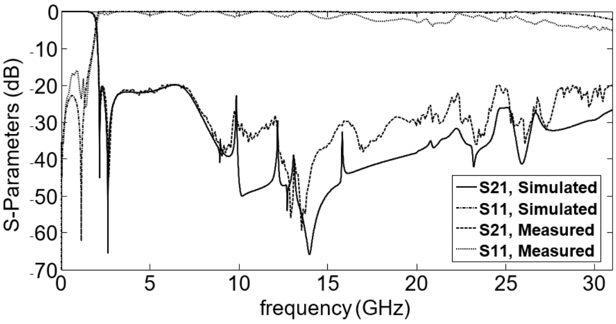

Fig. 10: *Experimental results of the S parameters for the proposed low-pass filter.*

bandwidth by 14 times the cut-off frequency. The filter designed in this paper has a simple structure that facilitates its manufacture and production. Matching the results of the filtered simulation and comparing them with those of previous structures demonstrates the optimal performance of the filter. The distinctive feature of this filter is its high figure of merit of 32317, and can be used in modern communication systems along with the desired loss and proper return.

REFERENCES

[1] J.-S. Hong and M.J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, NY, USA: John Wiley & Sons, 2001.

[2] A. I. Loinaz and C. d. R. Bocio, “EBG at Microwave Frequency Range: Bragg and/or Resonant Effect?,” *Microwave and Optical Technology Letters*, vol. 42, no. 5, pp. 383–385, Sep. 2004.

[3] F.-R. Yang, Y. Qian, and T. Itoh, “A novel uniplanar compact PBG structure for filter and mixer applications,” in *1999 IEEE MTT-S International Microwave Symposium Digest*, vol. 3, 1999, pp. 919–922.

[4] Y. Rao, H. J. Qian, B. Yang, R. Gómez-García, and X. Luo, “Dual-Band Bandpass Filter and Filtering Power Divider With Ultra-Wide Upper Stopband Using Hybrid Microstrip/DGS Dual-Resonance Cells,” *IEEE Access*, vol. 8, pp. 23624–23637, 2020.

[5] L. H. Weng, Y.-C. Guo, X.-W. Shi, and X.-Q. Chen, “An overview on defected ground structure,” *Progress In Electromagnetics Research B*, vol. 7, pp. 173–189, 2008.

[6] M. N. Jahromi, “Wide stopband compact microstrip lowpass filter using circular ring resonator and split ring resonators,” *Microwave and Optical Technology Letters*, vol. 53, no. 9, pp. 1961–1964, Sep. 2011.

[7] H. Taher, “High-performance low-pass filter using complementary square split ring resonators defected ground structure,” *IET Microwaves, Antennas & Propagation*, vol. 5, no. 7, pp. 771–775, May 2011.

[8] A. S. Mohra, “Microstrip low pass filter with wideband rejection using opened circuit stubs and Z-slots defected ground structures,” *Microwave and Optical Technology Letters*, vol. 53, no. 4, pp. 811–815, Apr. 2011.

[9] V. K. Velidi, “Dual-Transmission-Line Microstrip Equiripple Lowpass Filter with Sharp Roll-Off,” *ETRI Journal*, vol. 33, no. 6, pp. 985–988, Dec. 2011.

[10] J. Ni and J. Hong, “Compact Continuously Tunable Microstrip Low-Pass Filter,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 1793–1800, May 2013.

[11] V. K. Velidi and S. Sanyal, “Sharp Roll-Off Lowpass Filter With Wide Stopband Using Stub-Loaded Coupled-Line Hairpin Unit,” *IEEE Microwave and Wireless Components Letters*, vol. 21, no. 6, pp. 301–303, Jun. 2011.

[12] M. Hayati, F. Shama, and H. Abbasi, “Compact microstrip lowpass filter with wide stopband and sharp roll-off using tapered resonator,” *International Journal of Electronics*, vol. 100, no. 12, pp. 1751–1759, Dec. 2013.

[13] K. Ma, K. S. Yeo, and W. M. Lim, “Ultra-wide rejection band lowpass cell,” *Electronics Letters*, vol. 48, no. 2, pp. 99–100, 19 January 2012.

[14] J. Wang, L.-J. Xu, S. Zhao, Y.-X. Guo, and W. Wu, “Compact quasi-elliptic microstrip lowpass filter with wide stopband,” *Electronics Letters*, vol. 46, no. 20, pp. 1384–1385, 30 Sep. 2010.

[15] M. Hayati, H. Asadbeigi, and A. Sheikhi, “Microstrip lowpass filter with high and wide rejection band,” *Electronics Letters*, vol. 48, no. 19, pp. 1217–1219, 13 Sep. 2012.

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