Notched UWB filter using exponential tapered impedance line stub loaded microstrip resonator

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Abstract: In this study, two ultra-wideband (UWB) filters having the fractional bandwidth \(>120\%\) are designed, analysed and fabricated. The first filter is designed with three quarter-wavelength short-circuited stubs and second by using exponential tapered impedance line stub loaded microstrip resonator. The first filter consists of five transmission poles within the passband. The second filter with tapered inductive loading on quarter-wavelength high impedance line exhibits a sharp notch stopband around 5.5 GHz, to suppress the interference from IEEE 302.11a WLAN band signals with an attenuation level \(>30\) dB. A good agreement between the measured and predicted results is achieved, which validate the authors’ filter designs.

1 Introduction

A wideband or ultra-wideband (UWB) bandpass filters with compact size, improved selectivity, better passband and least varying group delays are the main requirements to realise UWB and other radio communication systems. There are various well-known techniques to design wideband microwave filters [1–4]. Parallel-coupled line, hairpin-line, interdigital line and combine filters are wideband bandpass filters, which are known for their low cost and simple fabrication process [1]. However, their designs have coupling gaps which are very tight and this results into higher fabrication tolerances when a large fractional bandwidth (FBW) is desired, e.g. \(>50\%\). The tight coupling gaps have been greatly relaxed by opting parallel-coupled three-line microstrip structures [2] where four wideband bandpass filters with FBWs from 40 to 70\% are presented. In [3], wideband and small-sized ring filters with FBWs of \(>100\%\) have been introduced. A UWB microstrip filter with an optimum FBW of \(>120\%\) is presented in [4] which is based on non-redundant unit elements or connecting lines.

Nowadays, multiple-mode resonators (MMRs) are the most commonly known UWB filters which have become very popular due to their simple design, compact structure and easy fabrication. The original idea of an MMR was presented in [5] and based on this concept, a UWB bandpass filter was reported in [6] for the first time in which five transmission poles were realised using two-pole parallel-coupled lines and three-mode MMR. The work of [6] was utilised in [7] for designing a UWB filter with a better feasibility by using aperture on the backside ground plane which improved the coupling between resonator and feeders. A UWB filter is proposed in [8] by implementing network analysis theory and optimisation in Z-domain. The same concept with a modified theory is employed in [9], where transmission zeros have been produced on both sides of passband by shifting two-section open-circuited stubs.

In the UWB region, there are several other narrowband radio signals, including wireless local area network (WLAN), which operate at 5.5 GHz. Therefore, a lot of attention has been paid to design single- or multi-notched-band UWB filters [10–17]. To suppress the undesired WLAN radio signals, a meander line slot is employed in [10] and a narrow notched band is achieved in [11] by using embedded open-circuited stubs. In [12], embedded open stubs with U-shaped defected ground structure (DGS) are introduced to achieve a notch characteristic in the desired frequency band. Notched UWB filters were designed using complementary single split-ring resonator (CSSRR) in the ground plane [13] and the spurline structure in the main line [14]. A dual-notched bands UWB bandpass filter based on a simplified composite right/left-handed resonator and a triple-notched bands UWB bandpass filter using triple-mode stepped impedance resonator, are developed in [15, 16], respectively. A multi-band UWB filter with five short-circuited stubs and three U-shaped open-circuited stubs is proposed in [17].

In this work, we introduce a UWB filter with FBW \(>120\%\) first by a uniform 50 \(\Omega\) transmission line loaded with three identical and symmetrical quarter wavelength short-circuited stubs. Finally, to suppress WLAN radio systems, we have developed a novel notched UWB filter using exponential tapered impedance line stub loaded microstrip resonator (ETILSLMR). The sharp notch frequency at 5.5 GHz is obtained with the help of tapered inductive loading on quarter wavelength high impedance line. Two prototype filters, first without notch band and second with a notch stopband, are fabricated and a good agreement is achieved between their measured and predicted results.

2 Initial UWB filter design

The schematic of the initially designed UWB filter is shown in Fig. 1. It consists of a uniform 50 \(\Omega\) transmission line in the horizontal plane and three quarter wavelength short-circuited stubs loaded in the vertical plane. One of the stubs is in the middle position of one side of 50 \(\Omega\) transmission line and the other two, which are of the same dimensions, are at the symmetrical locations on the other side of the transmission line. All the stubs are placed at a distance of about a half wavelength apart from each-other to realise five transmission poles within the passband. Due to the same dimensions of each stub, two transmission zeros, one at the zero frequency and another in the upper stopband with greater selectivity has been achieved. The optimised design parameters for the proposed filter are provided in Table 1 and its simulated results obtained from HFSS software are shown in Fig. 2. The passband for this UWB filter ranges from 2.6 to 10.6 GHz with FBW of 121\% at a centre frequency of 6.6 GHz. It can be seen that \(S\)-magnitudes, \(|S_{21}| > -3\) dB and \(|S_{11}| < -10\) dB in the whole passband. The filters are designed on the FR4-epoxy substrate \((\epsilon_r = 4.4, \tan \delta = 0.02, h = 1.6\) mm). The diameter of each via-hole is 1.1 mm.

2.1 Theoretical analysis of proposed UWB filter

By using transmission line network analysis, an approximate theoretical analysis is performed for the UWB filter design. It is considered that transmission lines are lossless and ignores the effects of edge capacitances at the junctions, inductive effects at...
the short-circuited stubs and frequency dispersion. The overall 
ABCD matrix, \([R]\) for the transmission line model in Fig. 3, is 
obtained by multiplying the \(ABCD\) matrices of the terminal lines, 
shunt short-circuited stubs and connecting lines in sequence, i.e.
\[
[R] = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} U \\ V \\ W \\ U \end{bmatrix} \begin{bmatrix} V \\ W \\ V \\ U \end{bmatrix}
\]
(1)

where
\[
[U] = \begin{bmatrix} \cos(\theta_0) & jY_0 \sin(\theta_0) \\ jY_0 \sin(\theta_0) \cos(\theta_0) \end{bmatrix}
\]
(2)
\[
[V] = \begin{bmatrix} 1 \\ Y_0 \tan(\theta_1) \\ jY_0 \end{bmatrix}
\]
(3)
\[
[W] = \begin{bmatrix} \cos(\theta') & jY_0 \sin(\theta') \cos(\theta') \\ jY_0 \sin(\theta') \cos(\theta') \end{bmatrix}
\]
(4)

Using the matched source and load condition with impedances, 
\(Z_0\), the \(S\) parameters of the proposed model can be obtained from (1) as
\[
S_{11} = \frac{A + (B/Z_0) - CZ_0 - D}{A + (B/Z_0) + CZ_0 + D}
\]
(5)
\[
S_{21} = \frac{2}{A + (B/Z_0) + CZ_0 + D}
\]
(6)

The analytical results of the designed UWB filter are plotted and 
compared with simulation results, as shown in Fig. 4. A shift at 
higher frequencies is mainly observed in analytical results due to 
lossless transmission lines and frequency-independent dielectric 
material assumptions, which are frequency-dependent parameters

### Table 1 Design parameter values for the initial UWB filter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L)</td>
<td>38 mm</td>
</tr>
<tr>
<td>(W)</td>
<td>32 mm</td>
</tr>
<tr>
<td>(L_1)</td>
<td>6.5 mm</td>
</tr>
<tr>
<td>(W_1)</td>
<td>3.1 mm</td>
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<tr>
<td>(L_2)</td>
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<tr>
<td>(W_2)</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>(L_3)</td>
<td>18.75 mm</td>
</tr>
</tbody>
</table>

3 Notched-band UWB filter design

In order to design a UWB filter with notch characteristic, the 
designed UWB filter in the earlier section is modified by loading 
exponential tapered impedance line on each quarter wavelength 
short-circuited stub and the resonator is termed as exponential 
tapered impedance line stub loaded microstrip resonator (ETILSLMR). These tapered loadings result in higher inductive 
effects on resonators and it is found from a parametric study that a 
notch stopband at a desired frequency can be obtained in the 
passband depending on the design parameters of tapered line. The 
schematic design of notched-band UWB filter is shown in Fig. 5, and its optimised dimensions are listed in Table 2. All the electrical 
parameters of this filter design are same as an initial UWB filter; 
only tapered sections and their dimensions are added. The 
dimensions of exponentially tapered impedance line sections are 
optimised so that the proposed filter with notch band around 5.5 
GHz can effectively suppress the interference from WLAN 
devices. Fig. 6 shows the simulated results for the notched-band 
UWB filter. The attenuation in the notch band region is about 32 
dB, which is also sharp enough to suppress the interference from 
WLAN devices.

#### 3.1 Theoretical analysis of notched-band UWB filter

The impedance (or, admittance) of proposed ETILSLMR, as shown 
in Fig. 7, can be obtained from (7)–(9) as
and (4), and only U carried-out. The filter admittance of proposed ETILSLMR and their electrical ignoring the effects of step discontinuities, an approximate section exponential tapered impedance short-circuited stubs for theoretical analysis for notched-band UWB filter has also been realised notched-band UWB filter, which can be found as short-circuited stubs of quarter wavelength are replaced by two-

\[ Z_{\text{short}} = jZ_c \left( \frac{1}{1 - \delta^2} \right) \]

where \( Z_c(z) \) is the impedance of exponentially tapered line with the positive rate of taper \( \delta \) and \( R_z \) is the lowest to highest impedance ratio of the stub line \( (R_z = Z_c/Z_0) \). After defining the impedance (or, admittance) of proposed ETILSLMR and their electrical parameters, one can find the S parameters by using transmission line network analysis

\[ Z_{\text{short}}^{\text{inh}} = jZ_c \left[ \frac{R_z \tan \beta_z l_z \left( 1 - \frac{\delta^2}{4\beta_z^2} \right) - R_z\tan \beta_z l_z \left( 1 - \frac{\delta^2}{4\beta_z^2} \right)}{1 - \frac{\delta^2}{4\beta_z^2}} \right] \]

\[ Y_{\text{short}}^{\text{inh}} = -jY_i \left[ \frac{R_z \tan \beta_z l_z \left( 1 - \frac{\delta^2}{4\beta_z^2} \right) - R_z\tan \beta_z l_z \left( 1 - \frac{\delta^2}{4\beta_z^2} \right)}{1 - \frac{\delta^2}{4\beta_z^2}} \right] \]

With the same assumptions as taken in the previous section and ignoring the effects of step discontinuities, an approximate theoretical analysis for notched-band UWB filter has also been carried-out. The \([U]\) and \([W]\) matrices will remain same as above (2) and (4), and only \([V]\) matrix will be changed as only each shunt short-circuited stubs of quarter wavelength are replaced by two-section exponential tapered impedance short-circuited stubs for realising notched-band UWB filter, which can be found as

\[ [V] = \begin{bmatrix} 1 & 0 \\ Y_{\text{inh}}^{\text{short}} & 1 \end{bmatrix} \]

\[ (10) \]

Table 2 Design parameter values for the notched-band UWB filter

<table>
<thead>
<tr>
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<td>W₂</td>
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<td>18.75 mm</td>
<td>W₃</td>
<td>10 mm</td>
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<tr>
<td>L₄</td>
<td>3.25 mm</td>
<td>—</td>
<td>—</td>
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</table>

Fig. 5 Proposed notched-band UWB filter structure

![Proposed notched-band UWB filter structure](image)

Fig. 6 Predicted magnitude of S parameters for the notched-band UWB filter

![Predicted magnitude of S parameters for the notched-band UWB filter](image)

Fig. 7 Proposed two-section short-circuited transmission line structure

![Proposed two-section short-circuited transmission line structure](image)

Fig. 8 Comparison of simulation with analytical S-magnitudes for the notched-band UWB filter

![Comparison of simulation with analytical S-magnitudes for the notched-band UWB filter](image)

With the same assumptions as taken in the previous section and ignoring the effects of step discontinuities, an approximate theoretical analysis for notched-band UWB filter has also been carried-out. The \([U]\) and \([W]\) matrices will remain same as above (2) and (4), and only \([V]\) matrix will be changed as only each shunt short-circuited stubs of quarter wavelength are replaced by two-section exponential tapered impedance short-circuited stubs for realising notched-band UWB filter, which can be found as

\[ [V] = \begin{bmatrix} 1 & 0 \\ Y_{\text{inh}}^{\text{short}} & 1 \end{bmatrix} \]

\[ (10) \]

4 Comparison with measured results

For experimental verification, two prototype filters with optimised electrical parameters are fabricated using a conventional PCB technology and measured using ZVA 24 VNA. The fabricated filters are shown in Fig. 9. The via-hole grounds of 1.1 mm diameters are made through soldering and two SMA connectors at the input–output ports are connected for the measurement. The predicted and measured S-magnitudes and group delay for the initial UWB filter and notched-band UWB filter are plotted together in Figs. 10 and 11, respectively. A good agreement between the two results is achieved, which validate the proposed filter designs. The measured 10 dB passband for initial UWB filter ranges from 2.7 to 11 GHz with FBW of 121% at a centre frequency of 6.85 GHz, whereas in the case of notched-band UWB filter, the measured sharp notch stopband is achieved between 5.3 and 5.8 GHz and passband regions are covered in the two frequency bands, 2.3–5.3 and 5.8–11.7 GHz, respectively. The maximum predicted and measured group delay variation in their passband is about 0.35 ns for both filters. The proposed filters do not incorporate any defected ground structures and can be fabricated easily. The shift towards higher frequencies in measured results is observed primarily due to imprecise calibration set-up for the measurement, frequency-dependent losses of the dielectric
material and the connectors, and unexpected tolerances in the fabrication similar to what have been reported in [9, 11].

The notch band characteristics of proposed notched-band UWB filter is compared with the other reported filters, as depicted in Table 3. The rejection level of 25 dB with a good group delay (<0.2 ns) is achieved in [10], while in [11], two filters with better feasibility and narrower notch FBW of 4.6 and 6.5%, are developed. In [12], a narrow notch band of 30 dB attenuation with tight coupling gaps is observed. By placing CSSRR on the ground plane in [13], a good notch characteristic of 32 dB is obtained, while in [14], rejection level is 39 dB, which is highest among all but suffers from wider notch band and higher group delay. In this work, a good rejection level of 32 dB, better notch band FBW of 9% and <0.35 ns group delay is achieved. The proposed design does not employ any defected ground structures or embedded structures and can be used in UWB technologies with some trade-offs in its design and performances.

### 5 Conclusion

In this paper, we have proposed a novel ETILSLMR to design a notched-UWB filter. Initially, a UWB filter with FBW of 121% at a
centre frequency of 6.6 GHz is designed by loading three identical quarter-wavelength short-circuited stubs to the main 50 Ω microstrip line. Later on, to suppress interference from IEEE 802.11a WLAN band, a notched-band UWB filter is designed by tapered inductive loading on quarter wavelength high impedance line. An approximate theoretical analysis has also been carried out for both filters and consequently, two prototype filter designs are fabricated and measured for experimental verification. We have found good agreements among the analytical, EM simulated and measured results of the filters, which validate the proposed designs.

6 References