Compact 5G Hairpin Bandpass Filter Using Non-Uniform Transmission Lines Theory

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Abstract **─** A compact three order 5G low frequency band Hairpin Bandpass Filter (HPBF) is analyzed, designed and fabricated in this paper. The designed filter operates at 5G frequency range (5.975-7.125 GHz). 17.76% compactness in each λ/2 uniform transmission line (UTL) resonator of the filter is achieved by applying Non-Uniform Transmission Lines (NTLs) theory. This compactness will make modern wireless transmitter and receiver designs more compatible. Study on the best reduction size percentage and suitable constraints to design the required NTL resonator is highlighted in this paper. Six samples with different size reductions percentage are fabricated and measured. The simulation is carried out in this study uses High Frequency Structure Simulator (HFSS) software and Computer Simulation Technology (CST) software. The simulated results for UTL HPBF and NTL HPBF with the six cases are verified with measurement. For the best size reduction percentage design, the measured results demonstrated that the 6.55 GHz NTL and UTL HPBF show good impedance matching within the unsilenced 5G frequency band.

Index Terms **─** 5G, hairpin bandpass filter, HFSS and CST, non-uniform transmission lines theory, uniform transmission line.

I. INTRODUCTION

Filters play an important role in many RF/ Microwave applications which it is used to control the frequency responses (bandpass, bandstop, lowpass, and highpass). HPBF is a compact structure bandpass filter and simply constructed by folding the λ/2 resonators of the parallel coupled line filter, to get the U shape that eases its fabrication process where no grounding via holes are needed [1]. By controlling the filter resonators' parameters (length, width and space between them), the required pass band can be obtained [2]. At different frequencies of interest, HPBFs were used in many applications such as Ku-band satellite communication [3, 4], X-band radar navigation [5], (2 – 4 GHz) satellite application [6], 5th generation mobile communication system [7], narrow band communication (uplink frequency in the band -3 eNodeB LTE) [8], millimeter-wave applications [9, 10], 923 MHz RFID application [11] and WiMAX application [12, 13]. Hairpin units are used in [14] to get a wide stop band of 3.36 – 21.5 GHz with a sharp roll off skirt for 3.1 GHz lowpass filter. Defected Ground Structures (DGS) and Microstrip Structures (DMS) are used in HPBF design for performance enhancement and size reduction [15-19]. One of the major concerns in any RF front ends wireless communication system, is to miniaturize its devices. Many techniques were developed to reduce the size of HPBF such as using ground holes [11], high dielectric substrate [20], multilayers structure [3, 21, 22], Nonuniform Coupled Lines (NCLs) resonators [10], metamaterial complimentary split ring resonators [13], Inkjet Printing (IP) [23] and Integrated Passive Device Technologies (IPDT) [9]. In this paper, in order to reduce high cost and the difficulties of the previous methods with the aim to reduce HPBF size, NTLs theory [24-29] is applied for the first time to compact the HPBF size at 5G low frequency band of 5.975 – 7.12 GHz, available for unlicensed operations [30] without effecting its primary performance. Furthermore, a study to achieve the best size reduction percentage with the suitable constraints of NTL HPBF is highlighted.

II. NON-UNIFORM TRANSMISSION LINES (NTLs) THEORY

Higher performance, lower cost and compact size passive microwave components are important devices in the modern wireless communication system to be compatible with the recent industrial requirements. There are many approaches to achieve the required

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compactness by reducing the devices transmission lines size such as using NTLs. NTLs theory [24-29] has been applied to many microwave circuits in order to reduce their sizes. The idea behind this theory is to make the performance of NTL with reduced length (d), varying characteristics impedance Z(z) and propagation constant β(z), equivalent to UTL of length (d_0), constant characteristics impedance Z and propagation constant β over the desired frequency range. Both NTL and UTL are shown in Fig. 1. Z(z) can be expanded in a truncated Fourier series as:

$$\ln(Z(z)/Z_0) = \sum_{n=0}^{N} C_n \cos\left(\frac{2\pi n z}{d}\right), \quad (1)$$

where Z_0 is the characteristics impedance of UTL and N is chosen to be 10. NTL and UTL will have equivalent performance if their ABCD matrix parameters are equal. Figure 1 (b) shows how to get the ABCD parameters of NTL by dividing it into K UTL sections then finding the ABCD parameters of those UTLs, so the total ABCD matrix will be:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{i=1}^{K} \begin{bmatrix} A_K & B_K \\ C_K & D_K \end{bmatrix}, \quad (2)$$

where $A_i = D_i = \cos(\Delta\theta)$, (2.1)

$Bi = j\, Z(z)\, ((i-0.5)\Delta z)\sin(\Delta\theta)$, (2.2)

$Ci = \frac{j\sin(\Delta\theta)}{Z\,((i-0.5)\Delta z)}$, i = 1, 2,….K , $\Delta z = d/K$, (2.3)

and $\Delta\theta = \frac{2\pi}{\lambda}\Delta z = \frac{2\pi f}{c}\sqrt{\varepsilon_{eff}}\,\Delta z$, (2.4)

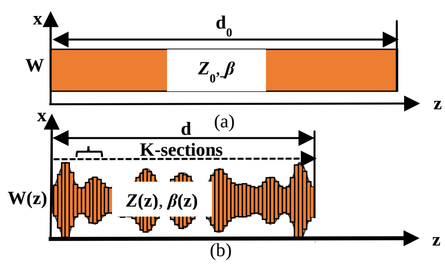


Fig. 1. (a) UTL and (b) NTL with its subdivision into K uniform sections.

The Z(z) coefficients C_ns are optimized using built in MATLAB function "fmincon" to minimize the following error function through the frequency band of 5.975 – 7.125 GHz:

$$\text{Error} = \sqrt{\frac{1}{M}\sum_{m=1}^{M}\frac{1}{4}\left(|A-A_0|^2 + Z_0^{-2}|B-B_0|^2 + Z_0^2|C-C_0|^2 + |D-D_0|^2\right)}, \quad (3)$$

where M is the number of the frequencies f_m (m = 1, 2, . . . M) within the desired band with frequency increment Δf and A_0, B_0, C_0 and D_0 are the ABCD matrix parameters of UTL. To restrict the error function in (3), two constraints should be considered: The resulting NTL should have the same width of UTL at the two ends to guarantee physical matching and it should be easy to fabricate. In this work, NTLs theory is applied to reduce the resonators' length of UTL HPBF without effecting its performance in terms of matching and transmission coefficients as will be explained in the next sections.

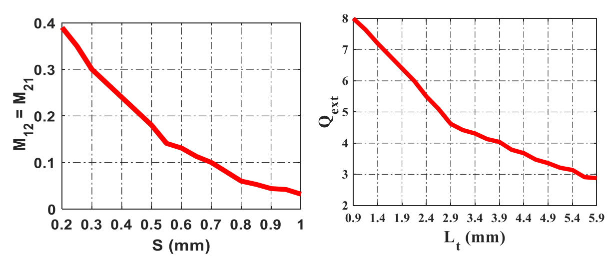
III. DESIGN OF THE PROPOSED 6.55 GHz UTL AND NTL HPBF

A. UTL HPBF design

Based on the design equations in [1], 6.55 GHz HPBF is deigned. In this study, the chosen substrate material is Rogers RO4003C (ε_r= 3.55 and h = 0.813 mm). Table 1 indicates all the calculated and optimized parameters of the filter, where Q_{ext}, M_{12}, L_{res}, W_{res}, S, L_t, L_{p1}, L_{p2} and W_p are external quality factor, coupling coefficient, the length of the resonator, width of the resonator, the space between two adjacent resonators, tapping length, length of the first and second port and width of the ports, respectively. Based on equations in [1], the relation between S and M_{12} and between L_t and Q_{ext} as shown in Fig. 2 is extracted using Full Wave Electromagnetic simulations such as HFSS. The optimized parameters in Table 1 are obtained via parametric studies to get better filter matching response as indicated in Fig. 3. The proposed UTL HPBF is shown in Fig.4.

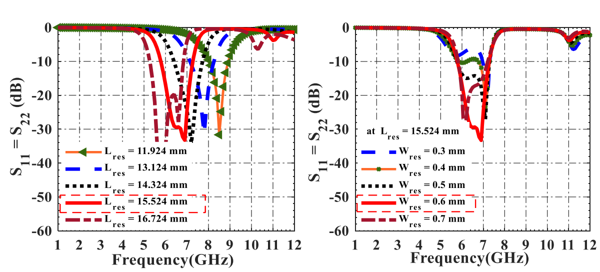
Table 1: Calculated and optimized parameters for 6.55 GHz UTL HPBF

Parameters	Calculated	Optimized
Q_{ext}	7.84	-
$M_{12} = M_{21}$	0.162	-
L_{res} (mm)	14.324	15.524
W_{res} (mm)	0.5	0.6
S (mm)	0.65	0.3
L_t (mm)	1.3	2.9
$L_{p1} = L_{p2}$ (mm)	-	4
W_p (mm)	1.819	1.819

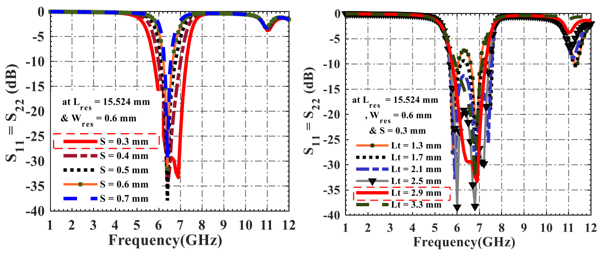


(a) (b)

Fig. 2. Relation between (a) M_{12} and S and (b) Q_{ext} and L_t.

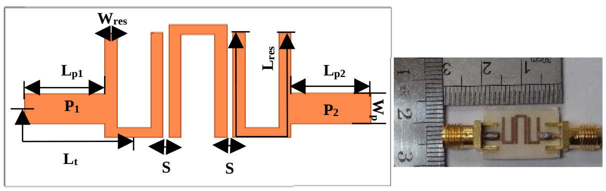


(a) (b)



(c) (d)

Fig. 3. Parametric studies of the proposed 6.55 GHz UTL HPBF on (a) L_{res}, (b) W_{res}, (c) S, and (d) L_t.



(a) (b)

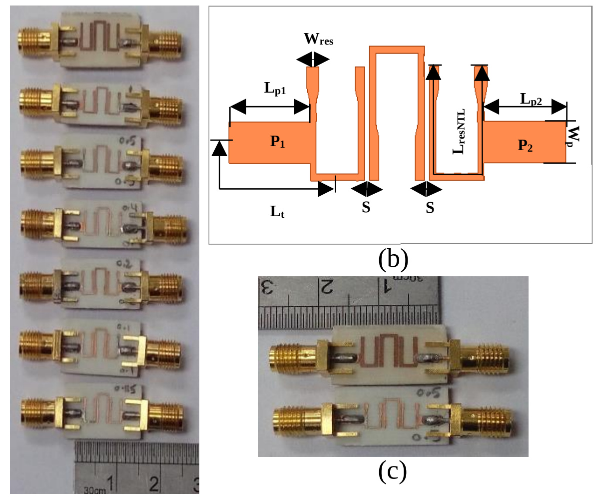
Fig. 4. (a) Layout of the proposed 6.55 GHz UTL HPBF, and (b) Fabricated prototype.

B. NTL HPBF design

Since modern 5G wireless system applications require compact microwave components, NTLs theory is applied to 6.55 GHz UTL HPBF resonators to reduce their sizes. Since W_{res} of UTL is 0.6 mm, so the width of NTL (W_{NTL}) should be between W_{res} and the minimum allowable width for fabrication, W_{min}= 0.3 mm. To test many cases with different size reduction percentages, in the MATLAB optimization code, the operation frequency band (5.975 –7.125 GHz) is relaxed to (5.5 –7.5 GHz) and different Δfs are used. As a result, six different samples of NTL HPBF are designed, fabricated and measured to test the best obtained size reduction percentage. Details on these cases and the required constraints are found in [29]. The measurement in this work is carried out uses N5245A network analyzer. The best achieved size reduction of 17.79% (i.e., the length of NTL resonator L_{resNTL} is equal to 12.766 mm) is obtained at Δf = 0.5 GHz. The optimized C_ns coefficients for this case is shown in Table 2. The six NTL HPBF porotypes as they are compared to UTL HPBF are illustrated in Fig. 5.

Table 2: Optimized Fourier coefficients for λ/2 6.55 GHz NTL HBPF's resonator

Constraints: $1.305 \leq \bar{Z}(z) \leq 1$					
C_0	C_1	C_2	C_3	C_4	C_5
-0.5196	-0.1508	0.2651	0.0146	0.0841	0.0978
C_6	C_7	C_8	C_9	C_{10}	
0.0362	0.0515	0.0718	-0.0111	0.0604	

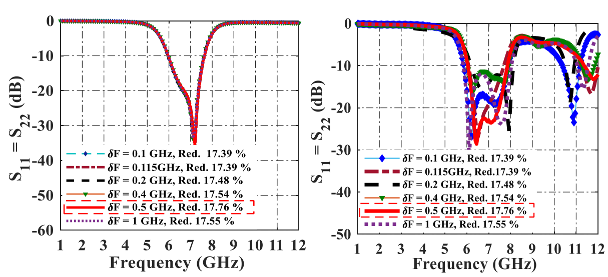


(a) (b) (c)

Fig. 5. (a) Fabricated prototypes of 6.55 GHz NTL HPBF at six different Δfs, (b) configuration of the proposed 6.55 GHz NTL HPBF at Δf = 0.5, and (c) fabricated prototypes of 6.55 GHz UTL and NTL HPBF.

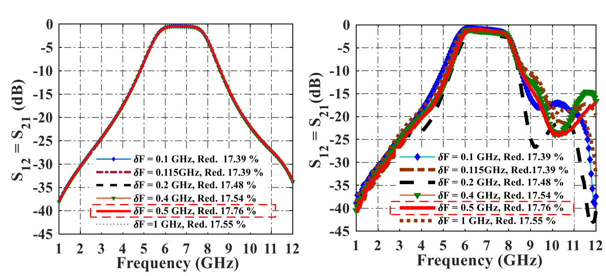
IV. RESULTS AND DISCUSSION

The simulated and measured reflection and transmission coefficients of the six samples are shown in Figs. 6 and 7, respectively. As it is clear all the samples give good impedance matching and transmission response through 5.975 GHz - 7.125 GHz.



(a) (b)

Fig. 6. (a) Simulated and (b) measured return loss of the proposed 6.55 GHz NTL HPBF for six different Δfs.



(a) (b)

Fig. 7. (a) Simulated and (b) Measured insertion loss of the proposed 6.55 GHz NTL HPBF for six different Δfs.

NTL HPBF results of the best obtained size reduction (17.79%) at Δf = 0.5 GHz is compared with UTL HPBF as shown in Fig. 8. Both filters provide good reflection and transmission coefficients. The comparison between the simulated and the realized results of 6.55 GHz UTL and NTL HPBF is given in Table 3. The slight difference between the simulated and measured results is due to the fabrication and measurement tolerances. Finally, as indicated in Fig. 8 (c), due to NTL and UTL resonators' lengths difference there is a slight difference in phase between the 6.55 GHz NTL and NTL HPBF. This difference has no big effect on the filter obtained matching and transmission performance which in turn indicates the effectiveness of applying NTLs theory to reduce the filter size.

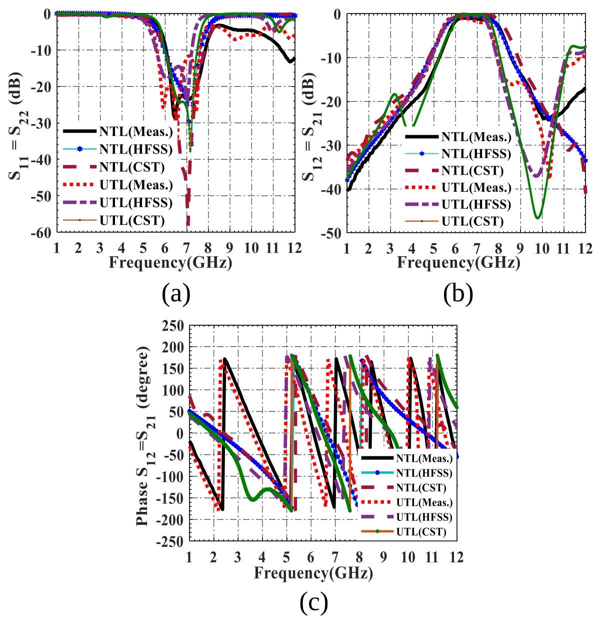


Fig. 8. (a) Return loss, (b) insertion loss, and (c) phase of 6.55 GHz UTL and NTL HPBF.

Table 3: Comparison between simulated and measured results for the designed UTL and NTL 6.55 GHz HPBFs

Parameters	Sim. (HFSS)	Sim. (CST)	Meas.
$S_{11} = S_{22}$ (NTL)	-22.7 dB at (5.99 - 7.34) GHz	-43 dB at (5.97 - 7.83) GHz	-22.52 dB at (6 - 7.86) GHz
$S_{11} = S_{22}$ (UTL)	-19.1 dB at (5.87 - 7.35) GHz	-25 dB at (5.96 - 7.48) GHz	-11.66 dB at (5.62- 7.6) GHz
$S_{12} = S_{21}$ (NTL)	-0.46 dB at Fc = 6.67 GHz	-0.29 dB at Fc = 6.9 GHz	-1.15dB at Fc = 6.93 GHz
$S_{12} = S_{21}$ (UTL)	-0.5dB at Fc = 6.61 GHz	-0.28 dB at Fc = 6.72 GHz	-1.17dB at Fc = 6.61 GHz

A comparison to other HPBFs in the literature at different frequency ranges in terms of techniques used for miniaturization, obtained size reduction percentage in λ/2 of the filter resonator's length, BW, filter response and circuit area is shown in Table 4, indicating that although the proposed filter uses simple miniaturization technique (NTLs theory) as compared to others, it provides low cost, better S_{11} and S_{12} and wider bandwidth. In addition, it provides better compactness in the resonator's length as compared to [10], [18] and [31].

Table 4: Comparison to other works in literature

Ref.	Technique Used	h (mm)/ε_r	Reduction % in λ/2 L_{res}	3 dB FBW, Freq. Band GHz	S_{11}= S_{22} (dB)<	S_{12}= S_{21} (dB)	Circuit Area λg x λg
This work	NTLs	0.813/3.55	17.76	26.95% 6 – 7.86	< -22.5	-1.15	0.64 × 0.23
[9]	UTLs using IPT on LCP	0.1/3.2	NA	15% 28.12 – 32.68	-18.9	2.41-	0.50 × 0.48
[10]	NCLs	0.127/2.94	9.2	3.45% 31.02 – 32.11	< -9	-3.5	2.16 × 0.25
[18]	UTLs with Square DGS	1.58/2.2	1.69	30.11% 9.11 – 9.39	−19.2	- 3.7	1.81 × 0.35
[23]	UTLs using IPDT	different/different	NA	0.83% 91.9 – 99.9	-10	-5	0.95 × 0.4 mm^2
[31]	UTLs with Square DGS	0.348/1.524	11.31	97.33% 2.82 – 3.02	-19.5	-1.6	0.87 × 0.29

* LCP-Liquid Crystal Polymer, NA-Not Available.

VI. CONCLUSION

Three order 5G Hairpin Band Pass Filter (HPBF) with compact size λ/2 resonators at frequency range (5.975 – 7.125 GHz) is analyzed, designed and fabricated. Nonuniform Transmission Lines (NTLs) theory is used effectively in this study to get simple compactness in the filter resonators' lengths without additional components for matching or bandwidth enhancement. A study on the best size reduction percentage and the suitable constraints to design NTL HPBF is highlighted in this paper. 17.76% size reduction is achieved in each λ/2 resonator's length of HPBF. The designed NTL 6.55 GHz HPBF provides good impedance matching, enhanced bandwidth and good rejection out of band up to 11 GHz. The realized slight difference between simulation and hardware measurement is due to fabrication and measurement processes errors. As a future work, many techniques can be applied to the proposed filter to get further harmonics suppressions.

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