Novel Left-Handed Unit Cell for Multi-Band Filtering Applications

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***Abstract*— In this paper, a new type of left-handed unit cell is proposed, designed for multi-band operation. The proposed unit cell consists of a grounded square metal patch, capacitively coupled to the ring loaded with a grounded inductive stub. By varying some geometrical parameters of the unit cell, its three passbands can be arbitrarily positioned. To demonstrate the applicability of the proposed unit cell, low-loss bandpass filter of the third order has been designed, which exhibits 43% 3-dB fractional bandwidth centred at 5.1 GHz. The proposed filter can be used in modern wireless communication systems that operate according to IEEE 801.11a and HyperLanII standards.**

I. Introduction

Metamaterials have recently attracted considerable attention because of their unusual magnetic and electric properties, generally not found in nature. The first theoretical speculation on the existence of left-handed (LH) media and prediction of their fundamental properties was done by Russian physicist Victor Veselago in 1967, [1]. By combining split ring resonator (SRR) with a metal wire into one unit cell, Smith and Shultz performed the first experimental verification of negative index of refraction and LH behavior, [2]. In mid 2002, three groups of researchers simultaneous proposed a new approach to design of planar LH metamaterials based on the dual transmission line concept, [3]-[5].

In the years to follow, different constitutive elements of the unit cells were proposed, such as the complementary split ring resonator (CSRR), as well as different spiral, fractal and multiple geometries, [6]-[9].

However, all of the geometries proposed so far suffered from relatively high insertion losses. Recently, this drawback has been overcome by the unit cell called ForeS, [10], [11]. Although very compact, ForeS exhibits low insertion losses and a large design flexibility.

As the number of different wireless systems and services is rapidly growing, frequencies become less available. The answer to this problem is multi-band operation of the modern wireless communication systems. However, it is often the case that non-harmonically related frequencies are available, which presents the problem for the design of conventional multi-band circuits. In order to meet these requirements, a novel multi-band LH unit cell for filtering applications is proposed in this paper. The proposed resonator exhibits three distinct passbands that can be independently positioned by changing some specific dimensions of the structure. The influence of different geometrical parameters to performances is analyzed in detail. To demonstrate the applicability of the proposed unit cell, a very wide bandpass filter of the third order is designed.

II. Configuration of the Unit Cell

The proposed unit cell consists of a grounded square metal patch, capacitively coupled to the ring loaded with a grounded inductive stub, Fig. 1., where g denotes the gap between the feeding microstrip line and the resonator, a is length of the side of the patch, s is the distance between the patch and the metal ring, l and w_s denote length and width of the inductive stub, w is line width of the ring, and d and c denote side dimensions of square vias positioned in the center of patch and at the end of the inductive stub, respectively. The proposed unit cell exhibits three distinct passbands and one deep pole positioned between the first and the second passband. The positions of all zeroes and poles can be changed independently by changing some specific dimensions of the unit cell: the dimensions of the inductive stub determine the position of the first passband, patch produces the second passband and the pole, and the ring influences the third passband.

To enhance the coupling and increase the inductance of the structure, the gap g, distance between the patch and the ring s and the width of the ring w are chosen to be the minimal available in standard PCB technology, i.e. equal to 100μm. The unit cell is realized on a 1.27mm Taconic substrate, with εr=9.8 and dielectric loss tangent equal to 0.009. Conductor losses are modeled by using bulk conductivity for copper. The initial length of the side of the patch is a=5mm and stub length and width are l=5.9mm and w_s=0.3mm, respectively. The overall dimensions of a single unit cell are equal to $\lambda_g/10$x $\lambda_g/5$ on a given substrate, where λ_g denotes the guided wavelength. In Fig.2 the response of the proposed unit cell is shown, determined by EMSight, EM simulator in Microwave Office.

It can be seen that the proposed geometry exhibits three distinct passbands that are not harmonics. The positions of these passbands can be independently controlled by changing geometrical parameters of the unit cell.

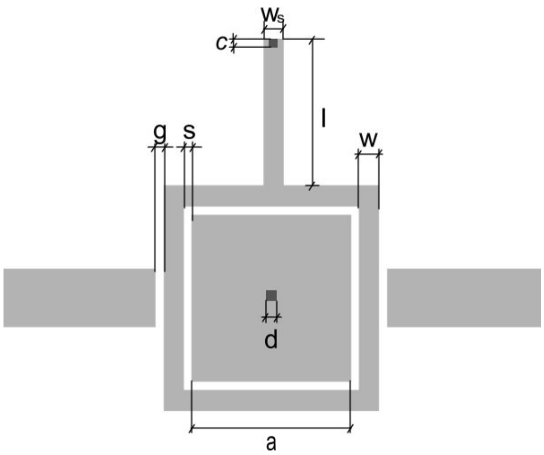

Fig. 1. Configuration of the proposed unit cell with all relevant geometrical parameters denoted

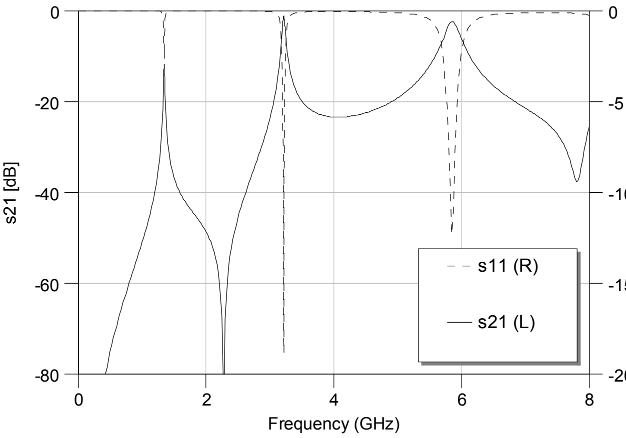

Fig 2. Simulated responce of the proposed unit cell

The position and characteristic of the first passband can be controled by changing dimensions of the inductive stub, namely stub width w_s and stub length, l. Simulation results for different dimensions of the stub are presented in Table I, where f_{r1} and f_{r2} denote central frequencies of the first and the second passband, BW denotes 3dB bandwidth of the first resonance, s_{21}^0 and s_{11}^0 are insertion loss and reflection of the first resonance, while Q_L and Q_U denote loaded and unloaded quality-factor, respectively. The first column, denoted with l=0 corresponds to the case when no inductive stub exists and only via is added at the side of the square patch. This also corresponds to the maximum value of the first resonance achievable with a given initial set of dimensions. By comparing it with another, randomly chosen, boundary set at l=5.9mm, it can be seen that the proposed unit cell exhibits frequency tuning range greater then 40%.

A good trade-off between the insertion loss and low resonant frequency for all stub lengths is obtained for stub width equal to 0.3mm. In Fig. 3, simulation results for different stub lengths are compared for fixed stub width equal to 0.3mm. It can be seen that the variations of stub dimensions significantly influence only the first passband. When the stub length increases or stub width decrees, the first resonance is shifted towards lower frequency, but at the price of increased insertion losses and reduced quality factor. At the same time, the second and the third passband are almost unaffected.

TABLE I
SIMULATION RESULTS FOR DIFFERENT DIMENSIONS OF THE INDUCTIVE STUB

l [mm]	**0**	**0.6**	**1.7**	**3.4**	**5.9**	**5.9**	**5.9**
w_s [mm]	**n.a.**	**0.3**	**0.3**	**0.3**	**0.1**	**0.3**	**0.5**
f_{r1} [GHz]	2.13	2.04	1.84	1.6	1.23	1.35	1.41
B [MHz]	20	19.55	18.95	15.5	19.08	14.47	13.54
f_{r2} [GHz]	3.44	3.42	3.35	3.28	3.2	3.22	3.22
s_{21}^0 [dB]	-14	-13.2	-12.1	-11.6	-15	-11.7	-10.9
s_{11}^0 [dB]	-1.96	-2.17	-2.49	-2.68	-1.72	2.63	-2.92
Q_L	106.5	104.3	97.1	103.2	64.47	93.3	104.1
Q_u	110.9	109.6	103.5	110.9	66.58	100.0	113.3

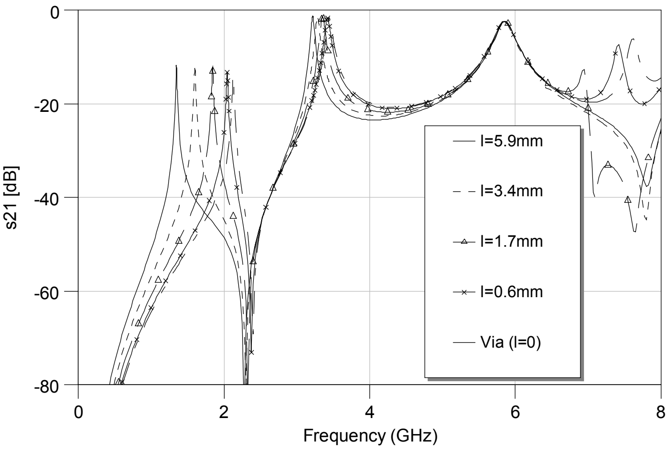

Fig. 3. Influence of the length of the inductive stub, l, to performances of the proposed unit cell, for a fixed stub width ws=0.3mm

The position of the second passband can be changed using two mechanisms: by changing the dimensions of the patch via, d, or by changing the size of the patch a. The stronger effect is obtained by changing via dimensions. Simulation results for the unit cell with tree different via sizes are compared in Fig. 4.

It can be seen that small changes in the dimensions of the patch via result in very large changes of the second resonance, as well as in the position of the pole. For example, by reducing via dimensions from 0.5x0.5mm to 0.1x0.1mm, reduction of more then 26% of the second resonant frequency is obtained. In the same time, there are no variations of the first and the third passband.

The influence of the patch size to performances is illustrated through comparison of the structures depicted in Fig. 5, where the patch size has been reduced at the expense of increased slot between the patch and the ring, s. The simulation responses of such structures are compared in Fig. 6.

It can be seen that the second passband and the pole are shifted towards higher frequencies when the dimensions of tha patch are decreased. However, due to the changed coupling between the patch and the ring, some variations in the position of the first and the third passband also exist.

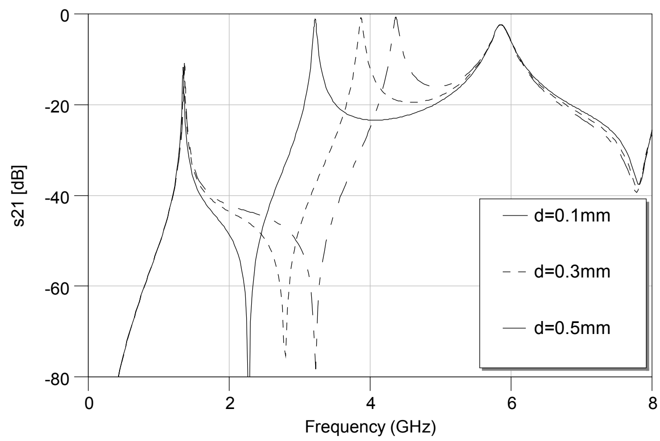

Fig. 4. Influence of the dimensions of the patch via, *d*, to performances of the proposed unit cell

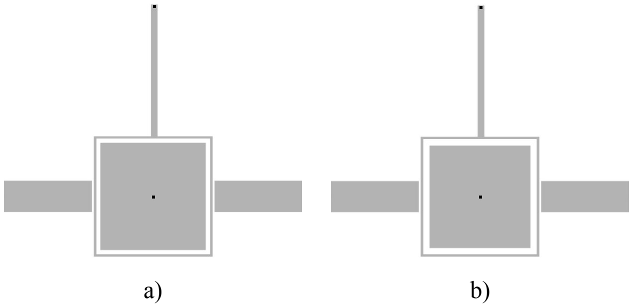

Fig. 5. Unit cells with different dimensions of the patch: a) a=4.8mm, b) a=4.6mm

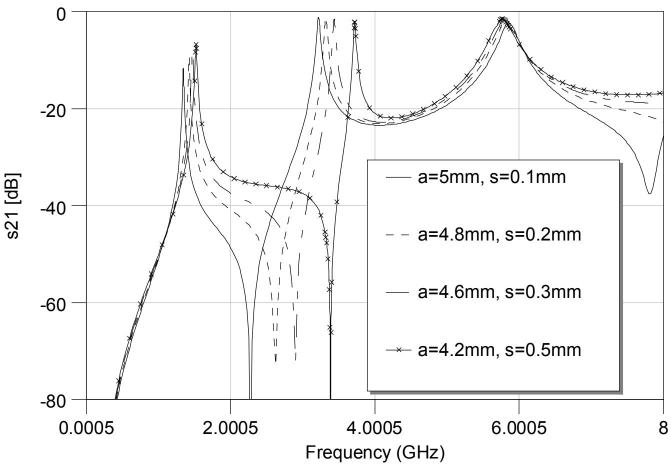

Fig. 6. Influence of the size of the square patch, *a*, to performances of the proposed unit cell

In order to reduce losses in the first passband or modify the shape of the transmission characteristic, coupling between the microstrip and the resonator can be changed. Three different geometries that use the same gap width *g* are analyzed, Fig 7, and their responses are compared in Fig. 8. Apart from the reduced losses, increased coupling results in a changed shape of the transmission characteristic. It seems that by a proper choice of the dimensions, the second and the third passband could be merged and a very wide passband could be obtained.

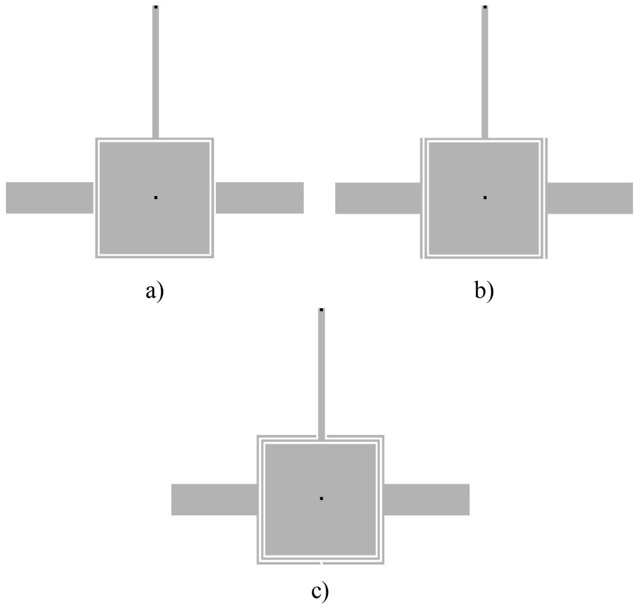

Fig. 7. Different coupling between the microstrip and the resonator: a) edge coupling, b) line coupling, c) maximal coupling

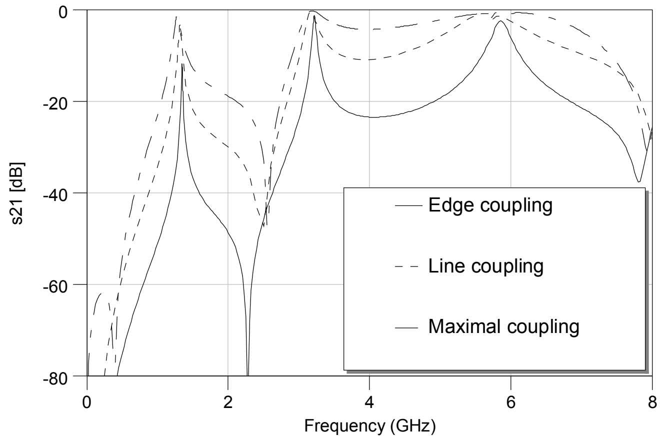

Fig. 8. Influence of the coupling between the feeding lines and the resonator on the transmission coefficient

III. Filter design

To illustrate the potential of the proposed unit cell in the arbitrary choice of the filtering characteristic, a very wide-band bandpass filter of the third order has been designed. Layout of the filter is shown in Fig 9 and the optimized dimensions are *d*=0.1mm, *a*=5mm and *l*=0.6mm.

Two stubs on the opposite sides of every unit cell are used to control the position of first band and insertion loss. By using two inductive stubs instead of just one, resistive losses are also connected in parallel which results in smaller insertion loss of the whole structure.

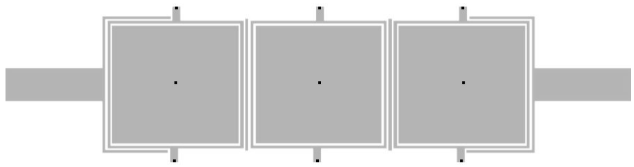

Fig. 9. Wide-band bandpass filter of the third order

By optimizing length of the inductive stub, the first passband was coincided with the pole and therefore suppressed for more then 30dB. In the same time, the second and the third passbands were merged to form a wide ripple-free passband. Further reduction of the stub length causes increased ripple in the passband.

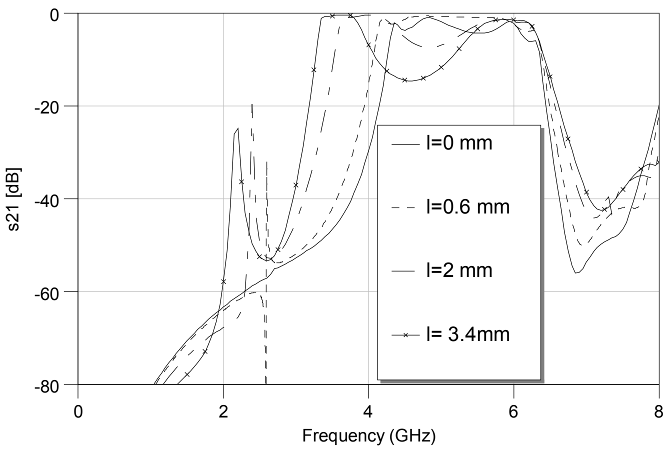

Fig. 10. Optimization of the stub length, *l*. Stub width is fixed at w_s=0.3mm

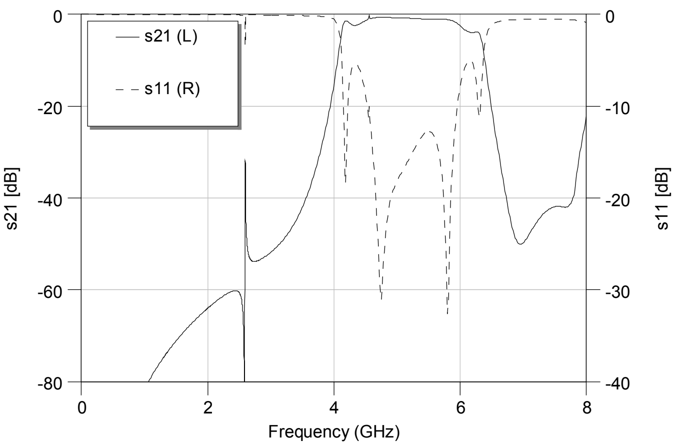

Fig. 11. Optimized response of the wide-band bandpass filter

The proposed filter is characterized by very low insertion loss equal to -1.05dB and a very wide passband with fractional 3dB bandwidth equal to 39% centred at 5.2GHz.

IV. CONCLUSIONS

Novel LH unit cell with multi-band characteristics has been presented. It has been shown through simulations that each passband can be independently controlled by varying specific dimensions of the unit cell. To illustrate the potential of the proposed unit cell, low-loss 39% wide bandpass filter of the third order has been designed. This filter could be used in IEEE 801.11a and HyperLanII systems.

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