New Bulk Metamaterial

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Abstract — **The design, analysis, fabrication and measurement of a new bulk metamaterial is reported in this paper. The structure of the new medium is made up of left-handed parallel strips. The series capacitors are realized by short circuited parallel strip stubs, and the conducting shunt pins represent parallel inductors. This metamaterial allows the propagation of a left-handed wave in the frequency band from 4.75 to 5.65 GHz, much wider than the frequency band achievable by split-ring resonators. The simple equivalent circuit of the metamaterial is derived. Additional modification of the media structure is proposed.**

I. Introduction

Left-handed (LH) metamaterials, i.e., materials with both negative permittivity and negative permeability have been of great interest to researchers in recent years, since it has become clear that they can be realized with sufficiently low insertion losses [1]-[3]. In the bulk version of the metamaterials [1],[3], the electromagnetic wave interacts with the embedded artificial inclusions and affects the macroscopic effective permittivity and permeability. A metamaterial with a specific response not found in nature can be produced. These metamaterials based on split ring resonators (SRR) are narrow band [1,3], since SRRs are resonant elements.

We have proposed, designed and fabricated a new bulk left-handed metamaterial. Its structure duplicates the concept of left-handed parallel strips cut by series capacitors and shunted by parallel inductors. The structure shows typical left-handed behaviour in a frequency band wider than the band of structures based on resonant elements [1],[3]. The wavelength of the excited LH wave increases with increasing frequency. This, together with the animation of the simulated electromagnetic field and the negative refraction of the wave confirms the left-handed character of the medium. The transmission and dispersion characteristics of this medium were calculated and measured. They fit each other very well.

II. Structure of the Bulk Metamaterial

The structure of the proposed metamaterial utilizes the concept of left-handed parallel strips. The cross section of the parallel strips is shown in the inset to Fig. 1. One of the strips is periodically cut by slots representing series capacitors, and the line is loaded by shunt pins representing parallel inductors, Fig. 1.

A unit cell of the proposed volume metamaterial is shown in Fig. 2. The wave propagates between the two

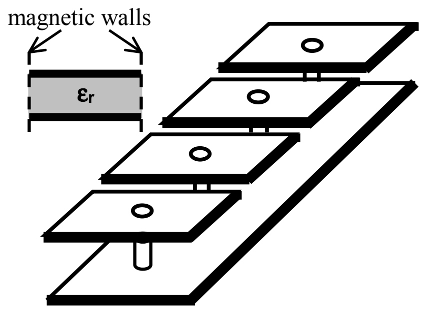

Fig. 1 LH parallel strips.

parallel metal strips a in width and $p+2t$ in length located at distance $2s$. There is a shunt pin of diameter $2r$ representing the parallel inductor at the center of the strip segments. The electric field vector of the propagating wave must be oriented, as shown in Fig. 2, across this parallel strips. The segment of the parallel strips is terminated by a junction where the two parallel strip short circuited stubs are connected to the line. Their length and height are h-s and p and their input impedance represents the series capacitor. The period of the structure in the direction of the wave propagation is $d = 2p+2t$. This motif of the cell containing the segment of parallel strips with the junction and two stubs is repeated in all three directions to create a volume structure. The incoming wave is thus incident at the matrix of the apertures of

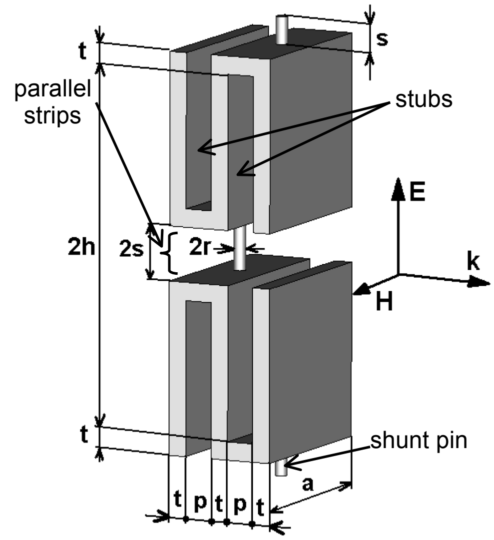

Fig. 2 A unit cell of the proposed bulk left-handed structure. Bold arrows show the orientation of the propagating wave vectors.

these cells. Fig. 2 shows only one central cell and two halves of the two neighbouring cells placed in the vertical direction. They are longitudinally shifted by one half of the period to fill the space completely. These cells are terminated by electric walls at their horizontal planes of symmetry.

The manufactured bulk LH metamaterial shown in Fig. 3 was milled from aluminium blocks. The background material is air, so $\varepsilon_r = 1$. The inductive pins are made of cylindrical wires fixed in holes drilled into the aluminium body. The dimensions of the structure were obtained by an optimization performed on the Microwave Studio simulator with the aim to obtain a structure with a wide frequency band of LH wave propagation, and at the same time to achieve minimum insertion losses. The resulting dimensions are $a = 20$ mm, $s = 5$ mm, $h = 24$ mm, $p = 3$ mm, $r = 0.5$ mm, $t = 2$ mm, $\varepsilon_r = 1$. The structure of 6x15 cells in the horizontal plane was investigated with electric walls placed from both sides, not shown in Fig. 3, i.e., in a waveguide of rectangular cross section.

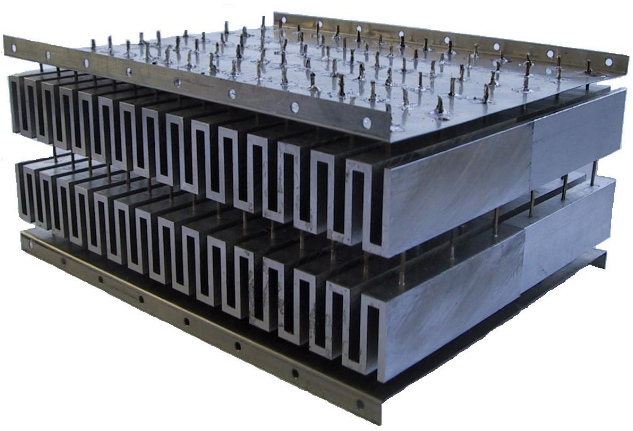

Fig. 3 Manufactured bulk metamaterial consisting of six parallel rows each of 15 cells.

III. Discussion of Results, Experiment

Fig. 4 shows the frequency dependence of the insertion losses of the structure from Fig. 3 calculated by the CST Microwave Studio, and also measured. The agreement of these curves is very good. The medium transmits a wave above 4.75 GHz. The frequency band of the LH wave propagation is apparent from the dispersion characteristic shown in Fig. 5. This band, in which the phase constant decreases and the wavelength rises with frequency, is between 4.75 and 5.65 GHz. The dispersion characteristic calculated by the CST Microwave Studio was verified experimentally, Fig. 5. The propagation constant was determined from the measured wavelength of the standing wave produced by a short located at an output plane. The frequency band of right-handed (RH) wave propagation is from 5.72 to 11.9 GHz. The bands of LH and RH propagation nearly merge, and cannot be distinguished in the transmission characteristic.

The negative refraction of the LH wave on the surface of the proposed metamaterial was also simulated by the CST Microwave Studio. The structure from Fig. 3 was terminated by a section of this metamaterial in the shape of a wedge. This wedge was modeled by step by step reduction of the width of each subsequent row by one cell. In this way we get a wedge with an angle of 64° towards the longitudinal axis, Fig. 6. There is a free space behind the wedge. The electric field distribution calculated at a frequency of 5 GHz showing negative refraction is plotted in Fig. 6.

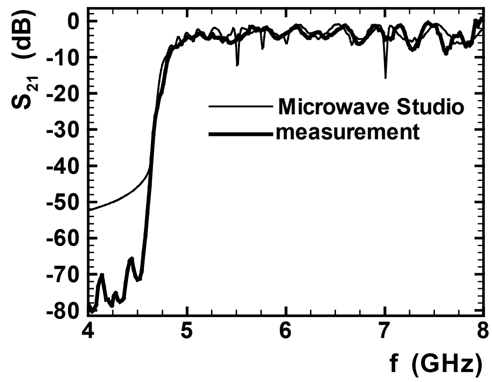

Fig. 4 S_{21} of the metamaterial from Fig. 3.

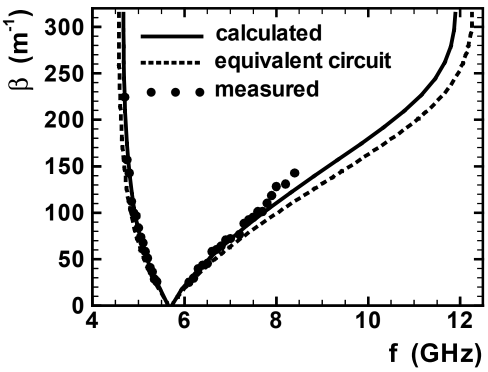

Fig. 5 The dispersion characteristic of the metamaterial from Fig. 3.

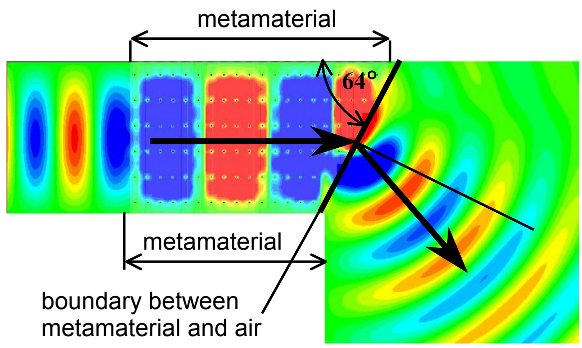

Fig. 6 The distribution of an electric field on the horizontal plane crossing the inductive pins at a central waveguiding part calculated at 5 GHz.

IV. Equivalent Circuit

The equivalent circuit of one cell of the metamaterial is shown in Fig. 7. The total length of the cell, which defines the period of the metamaterial, is $d = 2p+2t$, Fig. 2. The circuit consists of the hosting parallel strips divided into two parts $l/2 = p/2+t$ in length, Fig. 2, a series capacitor with capacity C, and a parallel inductor with inductance L. The characteristic impedance and the propagation constant of the hosting transmission line are [4]

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \frac{2s}{a} , \qquad (1)$$

$$k_0 = 2\pi f \sqrt{\mu_0 \varepsilon_0 \varepsilon_r} , \qquad (2)$$

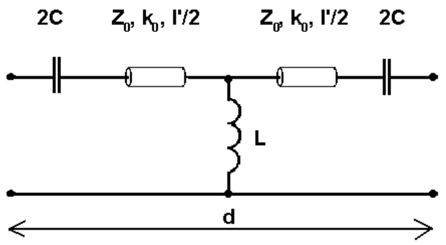

Fig. 7 The equivalent circuit of one cell of the metamaterial from Fig. 3.

where μ_0 and ε_0 are the permeability and permittivity of a vacuum. Series capacitance C is the input capacitance of the short circuited stub $l_s = h-s$ in length and p in height [4]

$$C = -\frac{1}{2\pi f \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \frac{p}{a} \tan[k_0 (h-s)]} . \qquad (3)$$

The cylindrical pin of length $2s$ and radius r represents parallel inductance L [5]

$$L = 2 \cdot 10^{-7} \cdot 2s \ln\left(\frac{2s}{r\sqrt{\pi}}\right) + 0.5 + 0.2235 \frac{r\sqrt{\pi}}{s} . \quad (4)$$

The dispersion characteristic of the infinite cascade of cells from Fig. 7 is determined by calculating the ABCD matrix of one cell and applying the Floquet theorem [4]

$$\cos(\beta d) = \cos(k_0 l') + \\ + \frac{ZY}{2} \cos^2\left(k_0 \frac{l'}{2}\right) + \frac{j}{2}\left(\frac{Z}{Z_0} + \frac{Y}{Y_0}\right) \sin(k_0 l') , \qquad (5)$$

where Z_0 and Y_0 are the characteristic impedance and admittance of the hosting parallel strips (1), $Z = 1/(j\omega C)$ and $Y = 1/(j\omega L)$ are the series impedance and the parallel admittance of the cell. l' is the modified length of the hosting parallel strips exceeding physical length l. The excess length l' is responsible for the reactance of the junction between the parallel strips and the stubs. Fitting characteristic (5) to the same characteristic calculated by the CST Microwave Studio resulted in $l' = l + 0.6p$. Fig. 5 shows the good accord between the propagation constant calculated by means of (5) and by the CST Microwave Studio, and the measured characteristic, except at high frequencies in the RH region. The propagation constant calculated according to (5) differs at high frequencies from the two remaining values, since the equivalent circuit increasingly loses its validity with increasing frequency.

V. Modification of the Metamaterial Structure

Fig. 2 shows the new LH medium with the air dielectric, and the structure is milled from blocks of metal. The side view of one cell of the modified LH medium is shown in Fig. 8, together with a model of it from the CST Microwave Studio. The structure is composed as a stack of dielectric slabs with permittivity ε_r. The parallel strip segments are formed by the metallized edges of the dielectric slabs. The space between these strips is filled with air. The junctions with the short circuited stubs are filled by the dielectric of permittivity ε_r. The shunt inductive pins lie on the surfaces of the dielectric slabs. The whole stack of slabs with tinned surfaces should be hot-pressed to be well connected. The dispersion characteristic of the LH wave propagating along one sequence of 30 cells, shown in Fig. 8, calculated by the Microwave Studio, is plotted in Fig. 9. This row of cells is terminated from the sides by magnetic walls. The corresponding scattering parameters calculated at the Microwave Studio are plotted in Fig. 10. The two plots in Fig. 9 and 10 show the same structure of pass- and stop-bands. This includes the stop-band, which spans from zero up to 8 GHz. The pass-band, at which the LH wave can propagate, spans from 8 up to 9.08 GHz. There is a stop-band above 9.0GHz and finally the RH wave can propagate at frequencies above 9.56 GHz. This RH pass-band is relatively flat up to 15 GHz.

The dielectric material in the proposed modified structure extends the possibilities for designing these artificial materials, e.g., it reduces the dimensions of the structure.

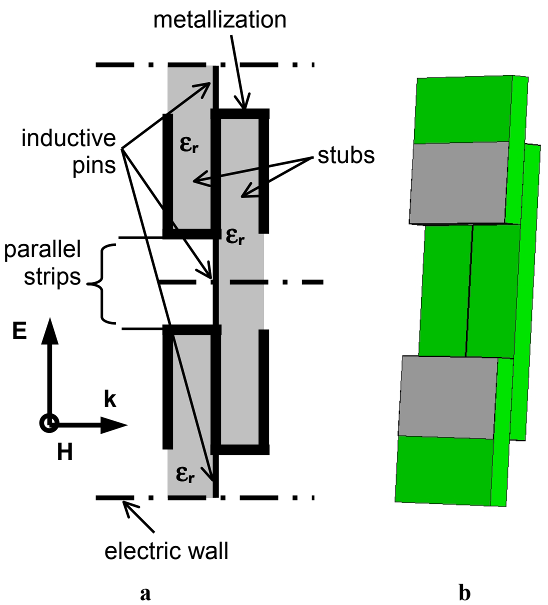

Fig. 8 A unit cell of the LH media with dielectric slabs, cross-section - a, model from the Microwave Studio - b.

VI. Conclusion

A new bulk metamaterial is proposed. Its structure incorporates the matrix of the left-handed transmission lines repeated both horizontally and vertically. These lines consist of parallel strip segments shunted at their centers by inductive pins representing parallel inductors. The segments are separated by short circuited parallel strip stubs representing series capacitors. The metamaterial exhibits left-handed behaviour in the frequency band from 4.75 to 5.65 GHz. The transmission and dispersion characteristics of this medium were calculated and measured. They compare very well with each other. In addition, the equivalent circuit of the metamaterial was proposed. This equivalent circuit models the metamaterial well. The new medium offers LH propagation in a wider frequency band than do metamaterials with split-ring resonators. It is a suitable candidate for applications when propagation of an LH wave is required. The application of dielectric slabs in a proposed modification of the metamaterial reduces the dimensions of the structure and increases the freedom in the design.

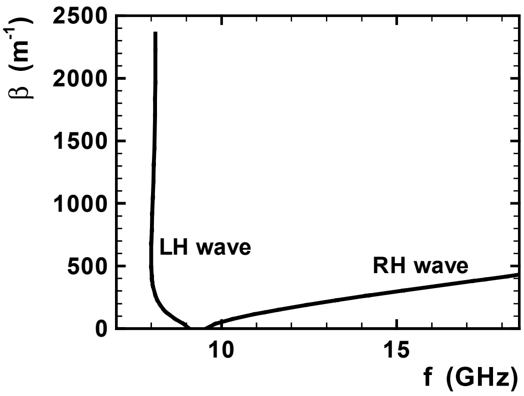

Fig. 9 The calculated dispersion characteristic of the two lowest waves propagating along the modified LH media from Fig. 8. The dimensions are $a = 10$ mm, $s = 5.5$ mm, $h = 12.5$ mm, $p = 0.635$ mm, $r = 0.075$ mm, $t = 0.035$ mm, $\varepsilon_r = 2.17$, as defined in Fig. 2.

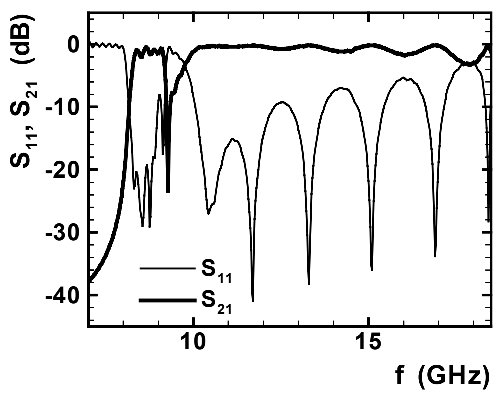

Fig. 10 Scattering parameters of the bulk metamaterial defined in Fig. 9 calculated by the CST Microwave Studio.

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