4. CONCLUSION

In this paper, a reduced-size novel periodic-waveguide resonant structure has been presented. It consists of a dielectric block that is transversely placed inside a rectangular waveguide formed in an MMIC substrate. The dielectric block supports periodic metallization patches. A bandpass filter at 74 GHz was designed and simulated and the simulated results were presented in order to verify the performance of the novel structure. This proposed configuration, results in the development of high-Q components, which are of great importance in filter applications at mm-wave frequencies.

REFERENCES


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values of their geometrical parameters are denoted by \( r_{11} \) and \( r_{22} \) with the internal ring split and denoted by \( r_{12} \) and \( r_{21} \) with the outer ring split. Moving the measuring loops between the transmitter and the receiver loops, both at a distance of about 300 kHz to 6 GHz using a network analyser. The measurement or by resetting the required combination of rings a few weeks later) was within the accuracy of the measurement, about 25 MHz.

4. THEORIES

4.1. Analytical

A simple analytical expression for the resonant frequency of the \( A_1B_3 \) configuration was given by Hardy and Whitehead [8] in the following form:

\[
\omega_0 = \left( c r_{21} \right) \left( 1 + r_{21}^2 \left( r_{11}^2 - r_{22}^2 \right) \right)^{1/2} / (\pi r_{12} r_{22}^2),
\]

(1)

where \( c \) is the velocity of light in vacuum. Their model assumed that the total magnetic flux within the internal cylinder is of the same magnitude and of the opposite sign as that between the two cylinders.

For the \( B_1B_2 \) configuration, the expression derived for the resonant frequency by Pendry et al. [6] is as follows:

\[
\omega_0 = (3d/\pi^2 r)^{1/2} (c/r),
\]

(2)

where

\[
d = r_3 - r_2, \quad r = (r_1 + r_2)/2.
\]

(3)

A more complex model relying on an equivalent circuit was proposed by Shamonin et al. [13, 14]. The equivalent circuit is a combination of lumped elements \( C_{se1} \) and \( C_{se2} \) (representing the gap capacitances for the outer and inner rings, respectively) and of distributed elements, like the inter-ring capacitance \( C \), the outer-ring inductance \( L_{1r} \), the inner-ring inductance \( L_{2r} \), and the mutual inductance \( L_{12} \) between the rings, all per unit radian. The equivalent circuit is then solved, subject to the boundary conditions. The resonant frequency is obtained as the solution of a transcendental characteristic equation. Within the limit of a sufficiently small resonant frequency, a simple approximate formula is obtained:

\[
\omega_0 = \left( 2 \pi L_{sw} \left( \pi C/2 + C_{se1} + C_{se2} \right) \right)^{1/2}, \quad L_{sw} = (L_1 + L_2)/2,
\]

(4)

which is the same as that obtained by Marques et al. [18] by heuristic arguments, except that the gap capacitances were disregarded. Note that the mutual inductance between the two rings does not enter the approximate formula.

A further expression for the lowest resonant frequency of the \( B_1B_2 \) configuration is given in a recent publication by Sauviac et al. [15] in the following form:

\[
\left( \omega_0 / \omega_0 \right)^2 = (1/2) \left( b - (b^2 - 4)^{1/2} \right),
\]

(5)

where

\[
b = (C_1L_1 + C_2L_2) \left( C_1C_2(L_1L_2 - L_{12}^2) \right)^{1/2},
\]

(6)

\[
C_1 = C_{se1} + (\pi C/2), \quad C_2 = C_{se2} + (\pi C/2).
\]

The capacitances and inductances for combinations (iii)–(v) are summarised in Table 1.
4.2. Numerical
The resonant frequencies of our five configurations were also obtained by numerical methods using a commercially available package called MICRO-STRIPES [21], which uses a 3D-TLM electromagnetic simulator. It analyses for a given electromagnetic input (a spatially constant, temporally varying magnetic field polarised in the direction of the axis of the rings) the electromagnetic response of a spatially discretised model. The object to be studied was enclosed into a computational window of $28.8 \times 28.8 \times 40 \text{mm}^3$, assuming absorbing boundary conditions at the boundary. The meshing was kept constant for all the structures and the rings were assumed to be lossless.

5. RESULTS
The experimentally found resonant frequencies are shown and compared in Table 2, both with the analytical results of Shamonin et al. [13, 14] and with the numerical results obtained using MICRO-STRIPES [21]. It may be seen that the lowest measured resonant frequency (1.44 GHz) is provided by the split-ring resonator (here referred to as the $B_1B_2$ configuration). The resonant frequency increases if only one of the rings is split. It is 2.78 GHz when the inner ring is split and 1.89 GHz when the outer ring is split. The resonant frequencies are also high for the singly-split single rings, $B_1$ and $B_2$. Again, it is higher (2.59 GHz) when the smaller ring is split than when the larger ring is split (1.74 GHz).

The numerical results, as may be expected, agree quite well with the experimental ones. The maximum deviation is about 2.5%.

There are no analytical results available for the singly-split single rings on their own. For the other three configurations, the analytical results are shown in the third column of Table 2. The analytically obtained resonant frequencies may be seen to be always above the experimental ones. They are within 5% for the $A_1B_2$ and $B_1B_2$ configurations, but the discrepancy is higher for $B_1A_2$.

For the $B_1B_2$ configuration, three further analytical approximations are available in the literature [6, 14, 15], as given by Eqs. (2), (4), and (5). The resonant frequencies are obtained from them as 1.61 GHz from Eq. (2), 1.35 GHz from Eq. (4) and 1.18 GHz from Eq. (5). The reason for the quite large discrepancy is that all three equations were derived with a number of simplifying assumptions.

An analytical approximation for the $A_1B_2$ configuration, provided by Eq. (1), is also available in [8]. It gives a resonant frequency of 6.4 GHz, which is quite far from the experimentally found 2.78 GHz. It may indeed be expected that the equation would give a result shifted considerably towards higher frequencies because the authors disregarded the interring capacitance, an approximation that was justified at the time for the resonators they designed.

6. CONCLUSION
Five different resonators, with each one of them containing at least one split ring, have been constructed from four basic elements and their resonant frequencies have been measured. The measured results have been compared with the numerical results for all five resonators and with the analytical results for three of the resonators. It has been shown that the experimental and numerical results are quite close to each other (2.5% at worst). The analytical results calculated from [13, 14] also show good agreement, but there is greater discrepancy when approximate formulae available from other publications [6, 8, 11, 15] are used.

ACKNOWLEDGMENTS
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TABLE 1 Values of Inductances and Capacitance Used in Calculations

<table>
<thead>
<tr>
<th>$L_1$, nH</th>
<th>$L_2$, nH</th>
<th>$L_3$, nH</th>
<th>$C$, pF • rad</th>
<th>$C_{s1}$, pF • rad</th>
<th>$C_{s2}$, pF • rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.90</td>
<td>2.74</td>
<td>1.99</td>
<td>0.239</td>
<td>0.106</td>
<td>0.092</td>
</tr>
</tbody>
</table>

TABLE 2 Values of Measured and Calculated Resonant Frequencies in GHz for the Various Resonators

<table>
<thead>
<tr>
<th>Resonator</th>
<th>Experimental</th>
<th>Analytical [13,14]</th>
<th>Numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1$</td>
<td>1.74</td>
<td>1.77</td>
<td></td>
</tr>
<tr>
<td>$B_2$</td>
<td>2.59</td>
<td>2.67</td>
<td></td>
</tr>
<tr>
<td>$B_1A_2$</td>
<td>1.89</td>
<td>2.17</td>
<td>1.94</td>
</tr>
<tr>
<td>$AB_1$</td>
<td>2.78</td>
<td>2.89</td>
<td>2.84</td>
</tr>
<tr>
<td>$B_1B_2$</td>
<td>1.50</td>
<td>1.438</td>
<td></td>
</tr>
</tbody>
</table>


21. MICRO-STRIPES is a registered trademark of Flomerics Ltd., Surrey, U.K.

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**EXPERIMENTAL DEMONSTRATION OF TRANSPARENCY IN THE ENG-MNG PAIR IN A CRLH TRANSMISSION-LINE IMPLEMENTATION**

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**ABSTRACT:** An experimental demonstration of transparency in the epsilon-negative (ENG) and mu-negative (MNG) pair using the composite right/left-handed transmission line (CRLI-TL) is presented. An eight-cell 1D microstrip transmission-line structure consisting of a ladder network of four CRLH unit cells with ENG characteristics connected to a ladder network of four CRLH unit cells with MNG characteristics is fabricated and tested. The transparency resulting from the cascading of MNG unit cells with ENG characteristics is observed in the S-parameter measurements and a circuit simulation of the voltage distribution.

**Key words:** left-handed (LH) metamaterials; composite right/left-handed transmission line (CRLH-TL); epsilon-negative (ENG); mu-negative (MNG)

1. INTRODUCTION

Recently, the concept of single-negative (SNG) materials, which are materials with negative permittivity and positive permeability,