Creating a simplified, frequency-tunable metamaterial

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A new method based on mechanical movement can tune the electromagnetic properties of metamaterials.

Metamaterials with periodically arrayed structures possess unique properties including, in certain instances, negative refractive indices. Possible applications of these artificial materials include high-gain antennas, superlenses, and cloaking devices. Normally, the electromagnetic properties of metamaterials depend on their structural parameters, which are fixed at the time of formation. New applications are possible if their electromagnetic properties can be modulated dynamically in real time.

Researchers have recently tried to create metamaterials whose resonance frequency can be tuned by adding extra parts, such as varactor diodes, ferro-electric materials, and liquid crystals. We have designed a metamaterial that can be tuned by introducing mechanical movement during its operation. The unit cell comprises two layers of substrates—with two etched copper rings opposite each other on the substrate surfaces. The thicknesses of the substrate and the metallic rings are 0.25 and 0.017mm, respectively. The two substrates can be driven to move relative to one another either along or perpendicular to gaps in the rings. When the structure is illuminated by a plane wave along direction $x$ with its electric field pointing along the gap’s direction, current flows along the rings, induced by the wave’s electric and magnetic fields.

Mutual capacitance occurs as the result of the coupling of the two metallic rings and can be changed when the two substrates are moved relative to one another. The resonance frequency decided by the effective capacitance can then be modulated, i.e., when working near the resonance frequency, the material’s resonance and other parameters can be tuned. This tuning method can also be illustrated by an equivalent circuit—see Figure 1(b)—in which $C_1$ to $C_4$ are the gap’s capacitances and $C_5$ to $C_7$ are the mutual capacitances between the two rings. $L_1$, $L_2$, $R_1$, and $R_2$ are the equivalent inductances and resistors. When moving one of the substrates, the gap capacitances remain constant while the mutual coupling capacitances change. Therefore, the resonance frequency ($\omega_0 = 1/\sqrt{LC}$) can be tuned. Because there are no extra parts involved, this tunable metamaterial can keep its original, simple construction.

Figure 1(a) shows a larger sample of the metamaterial formed with the unit cell arranged periodically. The two substrates can be moved relative to one another by an external force producing slip distances in the $y$ direction, shown as $S_y$. We expect that the resonance frequency will shift with different slips corresponding to the dynamic tuning of the electromagnetic parameters. Negative-material parameters can exist near the resonance-frequency range for metamaterials. Therefore, we expect that this negative region can be tuned.

Figure 2(b) shows calculated transmission spectra for different slip distances. It is clear that there are a series of resonance dips, which shift gradually from 9.6 to 7.7GHz when $S_y$ varies from 0 to 0.8mm. The two rings can be regarded as capacitors, and the...
capacitance decreases with increasing slip distance. Therefore, the resonance frequency will change downward. The retrieved permittivity—see Figure 2(c)—displays peaks corresponding to the resonance frequency. But the peaks shift to lower frequency gradually with $S_y$ increasing from 0 to 0.8mm. Also note that the negative permittivity indeed exists. As expected, the negative region also shifts with slip distance.

Finally, Figure 2(d) shows the resonance frequency for slip $S_y$. The data shows that the resonance frequency drops from 8.2 to 6.2GHz by changing $S_y$ from 0 to 0.8mm. For simplicity, we only show the results for displacements in the $y$ direction. We obtain similar data when we move the substrates along the $x$ direction.

In summary, we have demonstrated a frequency-tunable electromagnetic metamaterial based on mechanical movement. The method can be used effectively to tune the resonance frequency, as well as a material parameter (permittivity), without adding any extra parts. In our next steps, we will focus on designing reconfigurable antennas and tunable devices such as tunable filters and phase shifters at microwave frequencies.

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References