Design of volumetric sub-THz negative refractive index metamaterial with gain

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Abstract— Conventional passive metamaterials always suffer from the limitation of loss and dispersion due to fundamental causality issue. Especially it becomes severe due to material loss at terahertz frequency. Our work resolves the loss problem by introducing gain device into the metamaterial structure. A passive volumetric metamaterial is firstly designed on the quartz substrate. A negative resistance is inserted into the wire of the structure to provide the gain. We have identified resonant tunneling diodes that work up into THz frequency and shown in simulation that simultaneous negative index and gain can be obtained.

Keywords— active metamaterial; negative refractive index; sub-terahertz frequency

I. INTRODUCTION

Metamaterials (MTMs) are artificially designed, subwavelength sized composite structures which have exotic phenomena such as negative index of refraction, negative phase velocity that cannot be seen in nature. These artificial, unique media have been well studied theoretically and experimentally in the microwave region. However, MTMs are highly dispersive mediums and have narrow bandwidth with high losses. Designing MTMs with low absorption and high transmission is critical in many applications, such as cloaking, and perfect lens. The most promising method to control and compensate losses is inclusion of active devices into a MTM unit cell. Our previous works have both theoretically and experimentally demonstrated active metamaterials at microwave frequency with gain devices incorporated to compensate loss and potentially bandwidth limitations [1-4].

Metamaterial performance dramatically changes at terahertz (THz) region due to having intrinsic losses which makes usage of active devices inevitable in this frequency range. Therefore, we took one step further and extended our previous work into the THz region and we used effective negative resistance, the simplest equivalent circuit model of a THz tunnel diode, as an active device in the unit cell. The active design is specifically chosen to provide adequate loss over compensation to realize a MTM gain medium at sub-THz frequency range.

II. STRUCTURE DESIGN AND PARAMETERS RETRIEVAL

Fig. 1 shows the schematic of the structure that has been realized on a 100 μ m thick quartz substrate with a split ring (yellow color) and a wire (dark blue color) on each side of the substrate. Active unit cell can be achieved in various ways such as employing the negative resistance into the SRR to achieve active permeability or into the wire to achieve active permittivity. In this design we chose to implement the negative resistance into the wire.

Fig. 1. A schematic of MTM unit cell. (a) the front view. (b) A negative resistor ($-R = -175 \text{ Ohm}$) is embedded in the $5 \mu\text{m}$ gap of wire for the active design. (c) Side view of active/passive unit cell. The specific design parameters include $a=250 \mu\text{m}$, $b=500 \mu\text{m}$, $c=500 \mu\text{m}$, $k=75 \mu\text{m}$, $r_{\text{out}}=85 \mu\text{m}$, $r_{\text{in}}=60 \mu\text{m}$, $\text{wire1}=60 \mu\text{m}$, $\text{wire2}=40 \mu\text{m}$, $s=5 \mu\text{m}$, $\text{arm}=75 \mu\text{m}$, $\text{sub_height}=100 \mu\text{m}$.

The S -parameters for the passive and active unit cell are computed using ANSYS HFSS. For the active unit cell, lumped RLC boundary condition is used to implement a $-R = -175 \Omega$ in the wire. Properties of the MTMs are obtained by well-established retrieval procedure [5-7].

The retrieved passive unit cell index in Fig. 2(a) confirms that negative index (with significant loss) band lies in between roughly 147.8 to 153 GHz. As mentioned previously, active device implementation can be either in the split ring or in the wire. In this case, we choose to employ the active device (a simplified negative resistance) in the wire. The retrieved index of the active unit cell in Fig. 3(a) shows negative index that lies in the entire frequency of simulation. However gain medium is only achieved in the 151.8 - 155.7 GHz band.

Fig. 2. Passive unit cell parameters retrieval.(a) Refractive index of the passive effective MTM medium. Negative index is achieved in the 147.8-153 GHz band. (b) Effective relative permittivity and permeability of the passive MTM. The passive medium shows negative real part of permittivity below 179 GHz. Negative real part of the permeability is achieved in the 147.8 -153 GHz band.

Fig. 3. Active unit cell parameters retrieval. (a) Negative index of refraction is achieved in entire frequency of simulation. However the gain region is in the 151.8-155.7 GHz band. (b) Effective relative permittivity and permeability of the active MTM medium shows negative real and imaginary part in the entire frequency of simulation. Effective relative permeability of the active medium has only negative real part in the 150.9 - 156.4 GHz frequency range.

As shown in Fig. 3(b), the imaginary part of the effective permittivity is negative in the entire frequency range. It is obvious that it is due to the incorporation of the active device, $-R$, in the wire. Even though active device inclusion leads to very wide negative refraction index region, gain medium is only achieved in the double negative region

III. SUMMARY

In this work we demonstrated that negative index material can be obtained with a net gain when an active device implemented at the unit cell level in sub-THz range. Employing an active device (negative resistance) into MTMs not only can compensate / control losses but also can provide gain in the frequency of interest. This kind of metamaterials which can be achieved with active device that exhibits negative resistance in THz frequency range (e.g., THz tunnel or Gunn diodes with proper dc biasing) may be useful for implementing applications such as perfect lenses and invisibility cloaks where intrinsic losses fundamentally challenge their realizations.

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