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Terahertz composite right-left handed transmission-line metamaterial waveguides

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We report terahertz metamaterial waveguides based on the concept of composite right/left-handed transmission-lines. The waveguides are implemented in a metal-insulator-metal geometry fabricated with spin-coated Benzocyclobutene and contact photolithography. Angle-resolved reflection spectroscopy shows strong resonant absorption features corresponding to both right-handed and left-handed (backward wave) propagating modes within the leaky-wave bandwidth. Tuning of the waveguide dispersion is achieved by varying the effective lumped element series capacitance. The experimental results are in good agreement with full-wave finite element method simulations as well as an intuitive transmission-line circuit model. © 2012 American Institute of Physics. [doi:10.1063/1.3684250]

The terahertz frequency range (roughly 0.3-10 THz) is well suited for the fundamental exploration of electromagnetic metamaterial phenomena, such as negative index, ultra-high permittivity materials, and spoof-surface-plasmonic metamatic phenomena, such as negative index, ultra-wide bandwidth. Tuning of the waveguide dispersion is achieved by varying the effective lumped element series capacitance. The experimental results are in good agreement with full-wave finite element method simulations as well as an intuitive transmission-line circuit model.

While a CRLH transmission-line has been demonstrated near 400 GHz using a coplanar strip geometry,11 in the MIM geometry, the shunt capacitor $C_L$ is associated with a strong vertical electric field. Such a field is necessary to couple with the intersubband transitions in quantum cascade (QC) laser gain material, which enables the development of active metamaterial THz QC-laser metal-metal waveguides.12 For example, the forward scanning leaky-wave antenna demonstrated in Ref. 13 could be readily modified to exhibit CRLH operation by including a series capacitance. Here, we incorporate series capacitors into passive transmission-line metamaterial waveguides. Instead of epitaxial semiconductor quantum wells used in Ref. 13, Benzocyclobutene (BCB) polymer is used as the dielectric material. This material has modest loss values from 1-5 THz (Ref. 14) and can be spin-coated allowing comparatively inexpensive exploration of CRLH THz metamaterial waveguides on a wafer scale for prototyping designs for THz antennas, filters, and resonators.

The schematic of the fabricated waveguide is shown in Figs. 1(a) and 1(b). First a copper film is evaporated on a silicon substrate to serve as a ground plane, followed by the fabrication of the unit-cell. Figure 1(c) shows the calculated E-field intensity profile with HFSS for the fundamental mode (TM$_{00}$) and (d) odd mode (TM$_{01}$) in the x-z plane and at the edge of the unit-cell.

FIG. 1. (Color online) (a) Schematic representation (one unit-cell) of the designed CRLH metamaterial waveguides and their equivalent transmission-line circuit model. (b) Cross-section of the structure in x-y plane. Calculated E-field intensity profile with HFSS for (c) fundamental mode (TM$_{00}$) and (d) odd mode (TM$_{01}$) in the x-z plane and at the edge of the unit-cell.

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coating and curing of a 1 μm thick BCB film. This is followed by the evaporation and lift-off of 200 nm thick top Cr/Au pads, deposition of a 200 nm thick SiO2 layer, and finally 200 nm thick overlay Cr/Au patches. The 22 μm wide × 9 μm long top metal pads are each separated by a 3 μm gap. Cr/Au overlay patches are defined on top of the gap capacitor with a SiO2 layer to produce an appropriate series capacitance C_L.

In order to study the tuning properties of the CRLH behavior, we must realize both series capacitance C_L and shunt inductance L_L. The CRLH metamaterial waveguides are designed to operate in the odd lateral mode (TM_{01}) as shown in Fig. 1(d), which removes the requirement of a via to the ground plane.\(^{13}\) The width of the waveguide w is designed to be \(w = \lambda/(2n_{BCB})\) at \(f_{sh}\); this half-wavelength resonance condition determines the shunt resonant frequency \(f_{sh} = 1/(2\pi\sqrt{L_LL_C})\), which in turn determines the effective value of the shunt inductance \(L_L\). Its equivalent transmission-line model is given by the inset of Fig. 1(a). Design of waveguide dimensions was performed using transmission-line level analysis, with fine tuning provided by full-wave finite element method simulation (Ansys’, HFSS). The design was to obtain right-handed propagation above the shunt resonant frequency \(f_{sh}\) at 4.0 THz, and left-handed propagation below the series resonant frequency \(f_{sc} = 1/(2\pi\sqrt{L_CL_R})\), which is 3.7, 3.4, and 3.2 THz for S1, S2, and S3, respectively.

Fig. 2(a) shows the scanning electron microscope (SEM) images of a representative sample S1. The waveguide arrays are uniformly formed over an area of 1 cm × 1 cm. The array period in the transverse direction (z-axis) is chosen as 37 μm to avoid mode coupling from neighboring waveguides as well as grating lobes within the frequency range of interest. The inset shows a close-up view of the overlay patches separated from the top metal pads with the SiO2 layer. Fig. 2(b) shows a cross-section image of the series capacitor which was exposed by focused ion beam (FIB) milling.

The dispersion relations of the CRLH metamaterial waveguides were characterized with angle-resolved Fourier transform infrared (FTIR) reflection spectroscopy. The sample and detector were mounted on a θ-2θ rotary stage, which allows for a continuous incident angle scan from 10° to 90°. Due to the modification of the waveguide dispersion relation associated with the inclusion of the lumped elements \(L_L\) and \(C_L\), the propagating mode of the waveguide falls within the light cone \((|\beta| < \omega / c)\) for a finite bandwidth. Therefore, when the in-plane wave-vector of the incident light matches the propagation constant \(\beta\), incident light is coupled into the waveguide array via the leaky-wave mechanism. Due to metallic and dielectric losses, an absorption dip is present in the reflection spectrum. The FTIR broadband light was focused on the sample with an 8 in. focal length off-axis paraboloid mirror with a spot size of ~0.7 cm, slightly smaller than the sample size. This focusing scheme gives a variation of incident angle of less than ±3°, which causes a slight linewidth broadening not more than ~10% in the measured spectral features when estimated from the waveguide dispersion. The plane of incidence was kept perpendicular to the sample surface and parallel to the waveguide axis as shown in Fig. 3(a) inset. A wire grid polarizer was used to select either s- or p-polarization. The reflection from a gold mirror was used as the reference spectrum. The system was purged with N2 gas to minimize the effects of water vapor absorption, although small residual artifacts remain in measured spectra. All measurements were performed at room temperature.

Fig. 3(a) shows the reflection spectra of the S1 sample at different incident angles for incident s-polarization (electric field polarized transverse to the waveguide axis). The spectrum is characterized by two strong absorption features, each with a Lorentzian lineshape and a quality factor Q between 6 and 11. As the incident angle is increased from 10° to 80°, the higher frequency absorption dip blue-shifts from 3.9 to 5.3 THz, corresponding to right-handed propagating modes. Simultaneously, the absorption dip at lower frequency red-shifts from 3.7 to 3.3 THz, which corresponds to left-handed propagating modes with group velocity opposite to the phase velocity. A contour plot of the absorption of the sample is given by the inset, which clearly shows the right-handed and left-handed branches characteristic of a CRLH transmission-line. The observation of the CRLH dispersion characteristic for incident s-polarization is consistent with our understanding that the leaky-wave modes of this metamaterial waveguide radiate primarily through the lateral fringing fields associated...
with the shunt capacitance $C_R$ and couple with radiation polarized transverse to the waveguide axis in the far field.\textsuperscript{13,15} This is analogous to a microstrip patch antenna, where the patch supports a half-wavelength resonance, and the two “radiating slots” dominate the radiative process to produce a linearly polarized far-field beam.\textsuperscript{16} In our geometry, due to the lateral mode parity, incident s-polarized light will excite the odd lateral mode (TM$_{01}$) in the waveguide and not the fundamental mode (TM$_{00}$), which is necessary to observe full CRLH propagation. On the other hand, incident p-polarized light (electric field polarized along the waveguide axis) will couple to the series capacitors $C_L$ and will excite the fundamental TM$_{00}$ mode, whose intensity profile is shown in Fig. 1(c). Since this mode does not exhibit an effective shunt inductance $L_R$, only right-handed propagation is expected, with a cutoff frequency of $f_c$. This is confirmed experimentally, as shown in Fig. 3(b), where there is only one absorption dip which blue-shifts with increasing incident angle. Therefore, by selecting the polarization, one can excite either the TM$_{01}$ waveguide mode with CRLH behavior or the fundamental TM$_{00}$ mode with right-handed dispersion.

Fig. 4 illustrates the tuning of dispersion characteristics as the value of the series capacitance $C_L$ is changed by varying the overlay patch size. The circle data points are the center frequencies extracted from a Lorentzian fit to the measured reflection spectra. For incident s-polarization as shown in (a), as the patch size increases, the right-handed branch and left-handed branch shift towards lower frequencies. There is a 7% difference in the resonant mode frequency between experiments and full-wave finite element method simulations (not shown), which is attributed to fabrication non-idealities. As seen in the SEM images in Fig. 2(a), the rectangular metal pads are chamfered on their corners likely due to diffraction-induced pattern deformation during contact photolithography. Also, the overlay patches are shifted by $\sim$0.2-0.6 $\mu$m in the transverse direction and $\sim$0.6-1 $\mu$m in the longitudinal direction resulting from the non-ideal alignment. In addition, the SiO$_2$ layer plays a critical role in determining the $C_L$ value. Although not shown here, when the thickness of the SiO$_2$ layer was varied in the
fabrication process, a similar tuning of \( C_L \) was observed. To
gain physical intuition, we performed a least-squares fit of the
experimental results with a transmission-line circuit
model which gives a dispersion relation
\[
\beta(\omega) = \frac{s(\omega)}{p} \sqrt{\omega^2 L_R C_R + \frac{1}{\omega^2 L_C C_L} - \left( \frac{L_R}{L_L} + \frac{C_R}{C_L} \right)},
\]
where \( \beta \) is the propagation constant, \( \omega \) is the angular frequency,
\( p \) is the length of unit-cell, and \( s(\omega) = \begin{cases} -1 & \text{if } \omega < \min(2\pi f_{se}, 2\pi f_{sh}) \\ 1 & \text{if } \omega > \max(2\pi f_{se}, 2\pi f_{sh}) \end{cases} \). The results are given
by the solid curves in Fig. 4(a), and the fitting parameters (i.e., lumped element values) are listed in Table I. It is readily
seen that the circuit model reproduces our experimental results.
As the overlay patch size increases, the equivalent
left-handed capacitor \( C_L \) increases from 0.7 to 1.1 \( \mathrm{fF} \), which results in the red-shift of the dispersion curves. Fig. 4(b)
shows the tuning of dispersion curve for the fundamental mode, which corresponds to incident p-polarization. Again,
the experimental results are in good agreement with the
 circuit model, and the red-shift is mainly due to the increasing
\( C_L \) value. The measured dispersion and fitting indicate that
the S1 sample is at (or very close to) the CRLH balanced
condition, where \( f_{se} = f_{sb} \) and the transition between left-handed
and right-handed regions is smooth with no stop-band,
and a non-zero group velocity at \( \beta = 0 \). \(^9\)
Finally, as indicated in Table I, it is interesting to note that the odd lateral
 mode and the fundamental mode have very different
effective \( C_R, L_R, \) and \( C_L \) values due to their different properties.
A transmission-line model predicts identical series resonance frequencies \( f_{se} \) for both the fundamental mode and the
odd (differential) lateral mode. For the latter case, because of the two parallel transmission-line branches, we would
expect that \( 2C_{R,TM_{00}} = C_{R,TM_{01}}, L_{R,TM_{00}} = 2L_{R,TM_{01}}, \) and
\( 2C_{L,TM_{00}} = C_{L,TM_{01}} \). However, due to the sinusoidal lateral
E-field variation for the odd lateral mode, the effective capacitance seen by the mode is effectively less in each branch.
Hence the values of the lumped elements in Table I do not
simply vary by exactly a factor of two between the odd and
fundamental modes. This is an important consideration to
account for during structural design.

In conclusion, we have demonstrated CRLH metamaterial
waveguides in the THz frequency range. Angle-resolved
reflection spectroscopy measurements have revealed both
right-handed and left-handed propagating waveguide modes
in the leaky-wave bandwidth. This indicates the feasibility of
achieving both forward and backward wave beam steering
when used as a leaky-wave antenna. \(^{13}\) Also, we have shown
the tuning of the dispersion relation by varying capacitive
patch sizes, i.e., adjusting a lumped element value \( C_L \), which
suggests the possibility for adding tunability to functional
metamaterial waveguides. Although we have only mapped
the dispersion relation of leaky-wave modes, we expect that
there exists both right-handed and left-handed bound modes
outside the light line, i.e., spoof-surface-plasmons similar to
those observed on various structured metallic surfaces.\(^{3,17}\)
This geometry of waveguide is suitable for future implementation
with quantum cascade laser media, potentially enabling active THz CRLH metamaterial waveguides for active
leaky-wave antennas with forward to backward scanning.

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**TABLE I.** Fitting parameters for the circuit model plotted in Fig. 4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Patch dimension ( A ) (( \mu \text{m} ))</th>
<th>Odd mode ((\text{TM}_{01}))</th>
<th>Fundamental mode ((\text{TM}_{00}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( L_R ) (( p\text{F} ))</td>
<td>( C_R ) (( \text{fF} ))</td>
<td>( L_L ) (( p\text{F} ))</td>
</tr>
<tr>
<td>S1</td>
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<td>2.4</td>
<td>2.9</td>
</tr>
<tr>
<td>S2</td>
<td>7.6</td>
<td>2.4</td>
<td>3.0</td>
</tr>
<tr>
<td>S3</td>
<td>8.6</td>
<td>2.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

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\(^{10}\) C. Caloz, Mater. Today 12, 12 (2009).


