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Electromagnetic wave propagation through air-core waveguide with metamaterial cladding

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Abstract— Metamaterial-based waveguides offer unusual properties compared to conventional metallic and dielectric waveguides. We experimentally investigate a novel waveguide with an air-core and a cladding formed of slotted cylinder resonators, which can have an electric and/or a magnetic response at terahertz (THz) frequencies, depending on their orientation and the polarization of the light, and through these confine radiation to the hollow core. Various interesting phenomena are observed in the experiments including confinement of radiation through the electric response as well as the magnetic response, spatial dispersion, total internal reflection with refractive indices below 1, and slit resonances. Such waveguides promise future novel THz applications such as refractive index sensors or dispersion management.

Index Terms— Electromagnetic metamaterials, Terahertz metamaterials, Terahertz radiation.

I. INTRODUCTION

Metamaterials are artificially made materials with structures of a size much smaller than the wavelength of operation [1]. They offer the possibility of manipulating light in ways that are impossible with any known naturally occurring materials. The ability of metamaterials to bend light around obstacles, resolve features much smaller than the wavelength, or concentrate light to scales beyond what is allowed by diffraction, heralds revolutionary new technology and applications, some of which include microwave and optical cloaking devices [2,3], and super-resolved imaging [4].

The unprecedented control of the electromagnetic response of metamaterials has led to interest in developing metamaterial waveguides [5-10], which can potentially be important in various electromagnetic applications. Hollow waveguides are of particular interest for applications requiring high power-handling or gas sensing. It has been demonstrated that light can be confined in air by using a waveguide where the bounding medium, or cladding, is made of metamaterial [11-22]. Various kinds of metamaterial claddings have been presented such as self-rolling InGaAs/GaAs/Ag multilayers [21] and metal wires [22]. Interesting phenomena rarely observed in conventional waveguides have been shown in rectangular and circular waveguides with metamaterial claddings, including below-cutoff propagation [11,20], enhanced surface plasmon polaritons [16,17], fast and slow waves [14], and simultaneous transmission of backward and forward waves [15]. These novel properties could potentially lead to many application such as fluid sensing [17], super-resolved images through, for example, hyperlenses [21], and space-division multiplexing [12]. These studies on metamaterial waveguides have thus far been mostly numerical in nature, and there has been little experimental investigation, mainly due to the great challenge in fabrication.

Fiber drawing techniques have recently been demonstrated to fabricate large quantities of metamaterials with magnetic and electric responses [23,24]. Amongst the drawn metamaterials, examples containing longitudinally invariant slotted cylinder resonators (SCR) have been reported and characterized in terms of their magnetic response that depends on the geometry and size of the resonator.

Here, using fiber-drawn SCRs we fabricate an air-core planar waveguide with a metamaterial cladding consisting of arrays of SCR and characterize its response at THz frequencies. Specifically, we investigate the electromagnetic response of such SCR arrays, and the resulting waveguides and guidance mechanisms that these lead to. We observe, describe and characterize multiple interesting phenomena including confinement of radiation through both the electric and magnetic response of the metamaterial, total internal reflection with an air core through cladding refractive indices less than 1, and slit resonances. The outline of this paper is as follows: after describing the waveguide structure in Section II, the electric and magnetic response of the SCR arrays on their own are described and characterized in Section III. The combinations of
these arrays into the waveguide, the various ways in which guidance is achieved, and the various phenomena observed in the experiments are discussed and characterized in Section IV, followed by a discussion in the final section.

II. WAVEGUIDE STRUCTURE

The waveguide we consider is similar to a parallel plate waveguide, but with SCR arrays instead of metal plates, as shown in Fig. 1. The SCR used in this work consist of an indium slotted cylinder, encased in a polymer fiber made of polymethylmethacrylate on the interior of the metal cylinder and of polycarbonate on the exterior. A cross-section of the SCR fibers is shown in Fig. 1(a); the fiber diameter was 250 μm, the metal cylinder diameter was 200 μm, and the fibers remain invariant along their length. These SCR fibers were fabricated using fiber drawing as detailed in Ref. [24]. The fibers were arranged into two arrays of width \( w = 3.5 \) cm and length \( l = 4.6 \) cm, with each array containing approximately 140 fibers. The planar waveguide was formed by separating the two arrays by a distance \( d \), so as to form the air core.

![Image](image-url)

**FIG. 1.** (a) Schematic of the geometry of the air-core waveguide with metamaterial cladding. Note that the actual SCR arrays comprised 140 SCR fibers each, and the orientation of the slot in each resonator was random. (b) Optical microscope image of the cross section of the SCR. The bright part is metal and the material surrounding the metal is polymer. (c) The four configurations combining two propagation directions and two polarizations are also shown. They are relative to the waveguide shown in (a). (d) The magnetic resonance in the SCR may be excited either by a magnetic field parallel to the SCR axis, and/or by an electric field across the slot. Both result in the resonant current \( i \) indicated.

The SCR arrays can produce an electric response and metallic behavior, akin to an array of wires, and also a magnetic response like the more common split ring resonators (SRR), depending on the polarization of the radiation. As a result, the transmission properties of the waveguide will depend on the polarization and propagation direction of the radiation. Figure 1(c) shows the four possible configurations – labelled Case 1 to 4 – of two propagation directions (along or perpendicular to the axis of the SCRs) and two polarizations (TE or TM), which will be experimentally and numerically characterized. This simple geometry allows many interesting phenomena to be observed, including confinement of radiation through an electric response (metallic reflection) and a magnetic response, total internal reflection around the magnetic resonance frequency through refractive indices below 1, spatial dispersion, and slit resonances.

III. METAMATERIAL PROPERTIES

A. Resonant response

The magnetic response of the SCRs arises from a resonance which may be excited in two ways as shown in Fig. 1(d). A magnetic field \( H \) with a component parallel to the SCR axis [25] results in a change in the magnetic flux through the plane of the resonator. This produces an electric field and an oscillating current that result in a resonant response with a magnetic dipole moment parallel to the resonator axis. The same resonance also has an oscillating electric dipole moment between the edges of the slot, and can equally be excited by an electric field \( E \) with a component across the slot of the cylinder [26,27]. This resonance can be described by resonant permeability component parallel to the axis \( \mu_{zz} \), resonant permittivity component in the direction across the gap, and a resonant magneto-electric coupling coefficient between these two directions – which apply individually or simultaneously depending on the case considered in Fig. 1(c).

For example, the effective permeability component \( \mu_{zz} \) will have higher and lower real part at frequencies slightly below and above the resonance, respectively, and a maximum imaginary part at the resonance frequency. This will alter the effective refractive index of the array for frequencies around the resonance, which will affect the confinement of radiation in the present waveguide. Away from resonance the permeability is equal to that of free space and the dielectric in the structure will determine the index.

We characterized the transmission through the SCR arrays using terahertz time-domain spectroscopy (THz-TDS) in order to experimentally observe the magnetic resonance. A collimated THz beam was focused onto each array and the transmitted radiation was collected by a second lens. A schematic of the sample orientation relative to the polarization is shown in the inset of Fig. 2. The magnetic field was oriented along the SCR and perpendicular to the SCR plane, therefore the magnetic resonance may be excited as explained above. Furthermore, the electric field is in the SCR plane, and contributes to exciting the resonance through any field component parallel to the slot. As the orientation of the slot was not controlled in the array, on average half of the electric field is parallel to the slot. The transmittance, defined as the ratio of transmitted intensity with and without the SCR array in place, is shown as a function of frequency in Fig. 2. The SCR plate exhibits a transmission dip associated with the SCR resonance at 164 GHz. The sharp drop in transmittance is associated with the peak of the imaginary part of the permeability, permittivity and magneto-electric coupling at the center of the resonance, as well as with increased reflection due to the increased impedance mismatch around the resonance.
FIG. 2. Transmittance of SCR plate under TM illumination. The dip in transmittance at 164 GHz corresponds to the magnetic resonance. Inset: Schematic of the measurement.

B. Plasmonic response

As the SCR are longitudinally invariant and conducting along their length, electric fields with components along the cylinders will result in currents. As such, the SCR array will behave as a wire array and will exhibit metallic behavior with a permittivity described by a non-local Drude model and an effective plasma frequency which depends on the "wire" diameter and spacing. When the frequency is lower than the effective plasma frequency, the array will exhibit negative permittivity which will result in metallic reflection, while at higher frequencies it will exhibit positive permittivity. The effective plasma frequency \( f_p \) may be estimated using the following equation which describes arrays of wires \[ f_p = \frac{(c/n)^2}{\sqrt{3\pi a^2 \ln(a^2/b(2a-b))}} \] where \( c \) is the speed of light, \( n \) is the index of the dielectric, \( a \) is the spacing of the wires, and \( b \) their diameter. Equation (1) is only intended to be indicative in this context as it assumes thin wires compared to the wire spacing, whilst here an SCR array is being approximated as a wire array with wire diameter comparable to their spacing. Finally, electric fields perpendicular to the cylinder do not result in the current relevant to this electric response, and hence do not result in the metallic behavior.

The transmittance for the TE polarization was measured using the setup shown in the inset to Fig. 3, with the electric field parallel to the cylinders. Below the effective plasma frequency, metallic reflection results in low transmittance, whilst above the effective plasma frequency the dielectric behavior results in higher transmittance, giving high-pass filtering behavior. From the transmittance results in Fig. 3, the effective plasma frequency is found to be approximately 920 GHz. A comparison to Eq. (1), taking the index of the polymer to be 1.52, the “wire” spacing to be \( a = 270 \) \( \mu \)m, and diameter \( b = 200 \) \( \mu \)m, gives an effective plasma frequency of 1.18 THz, which is in reasonable agreement, despite the noted assumptions.

C. Spatial Dispersion

The invariance of the SCR along their length results in a non-local response, \textit{i.e.} spatial dispersion. Both, the resonant response and the plasmonic response are spatially dispersive. For the plasmonic response, the plasma frequency shifts to higher values with increasing wavevector component along the axis of the wires. We will only consider frequency ranges below the normal-incidence plasma frequency, so that the response will always be metallic for electric field components along the wires. The spatial dispersion effect for the plasmonic response at those frequencies will be weak in that radiation of this polarization will always be strongly reflected. In contrast, the effects of spatial dispersion will be very noticeable for the SCR’s resonance: the resonant frequency will strongly depend on wavevector [29], as will the effective \( \mu_z \). Qualitatively, the spatial dispersion shifts the resonance frequency from its normal incidence value \( f_0 \) to higher frequencies as the wavevector component along the cylinders increases, according to [29]:

\[
f(\theta) = \frac{f_0}{\sqrt{1 - \sin^2 \theta / n^2}}
\]  

where \( \theta \) is the angle indicated in the inset of Fig. 4, and \( n \) is the index of the dielectric (\( n = 1.52 \) here). Spatial dispersion with respect to wavevector components perpendicular to the axis of the SCR will be considered negligible, as the cross section and periodicity are much smaller than the wavelength.

Figure 4 shows the angle dependence of the magnetic resonance: With the magnetic field oriented parallel to the SCR, the sample was rotated to change the angle between the cylinders and the wavevector such that the wavevector component along the cylinders was changed. The resonant frequency increases with angle as expected, in agreement with Eq. (2).
FIG. 4. Transmittance through the SCR plate showing a shift of the magnetic resonance due to spatial dispersion. Inset: Schematic of the measurement.

D. Retrieved Parameters

To better understand the propagation mechanism of the waveguide, we retrieved the refractive index and impedance of the SCR plate for the TM polarization using the retrieval procedure detailed in [30]. The complex scattering matrix elements which describe the reflection ($S_{11}$ and $S_{22}$) and transmission ($S_{12}$ and $S_{21}$) of the field incident as shown in the inset in Fig. 2 were obtained from finite element calculations using COMSOL. In the simulation, periodic boundary condition was applied to the boundaries along x direction and Perfect Match Layers were added to the boundaries along the y direction (refer to the inset in Fig. 5(a). The bianisotropic behavior due to magnetoelectric coupling of our asymmetric resonant array was considered for the retrieval method since the orientation of the resonators is randomly distributed. The inset in Fig. 5 shows the simulation configuration: The diameter of the SCR was set to 250 $\mu$m to match the fabricated sample, the orientations of the slots are right, left, and downward, the length of the simulation domain in the direction of wave propagation (x direction) was 6 mm, which is larger than the wavelengths of interest, and periodic boundary conditions were set in the y direction.

Figure 5(a) and Fig. 5(b) show the retrieved refractive index and impedance of the SCR plate, respectively. The real part of the refractive index drops below 1 at the resonant frequency (164 GHz) and remains less than 1 until 230 GHz. When used as the cladding of a waveguide, a refractive index less than 1 can provide guidance by total internal reflection in a hollow core. Elsewhere, the SCR plate behaves like a normal dielectric with index greater than 1.

Since the SCR plate is thinner than the wavelength at the resonance frequency, the retrieved impedance is perhaps a more relevant parameter than the refractive index. A mismatch of impedance between the SCR plate and air will result in high reflection at the core-cladding boundary, and hence good transmission through the waveguide. Figure 5 (b) shows the backward impedance of the SCR plate when the waves travel in the -x direction. The forward impedance for waves traveling in the +x direction is omitted for clarity and is qualitatively similar to the backward impedance. Significant mismatch of the impedance between the SCR plate and air occurs for frequencies above 154 GHz, with the mismatch decreasing at higher frequencies approaching 250 GHz.

The effective refractive index and impedance values extracted here should be taken as a guide only, in the context of discussing reflection and thus guidance mechanisms. They are not a good indicator of bulk properties of a metamaterial made of SCRs as they are extracted for a single row only, and their only meaning is that they can be used to retrieve transmission and reflection.

FIG. 5. Retrieved refractive index (a) and impedance (b) of SCR plate. Inset of (a): Schematic of the simulated structure.

IV. CHARACTERIZATION OF THE WAVEGUIDE

Having characterized the SCR array, we now consider the waveguide they form. Several experiments with different values of the core size $d$ were carried out, with radiation from the collimated THz beam in the TDS system focused to the center of the core using a lens, with a waist adjusted to be similar to $d$ to maximize coupling while minimizing excitation of possible higher order modes. The output was collected and collimated by a second lens and directed to the detector. The transmittance is defined as the ratio of the intensity transmitted with the waveguide in place, and the intensity measured without the waveguide with one of the lenses shifted by the
length of the waveguide. Numerical modelling of the waveguide was also performed using COMSOL. The optical microscope image of the SCR (shown in Fig. 1) was imported into COMSOL to define the SCR, from which a model of the waveguide was constructed. Two differences between the experiment and these simulations are that the slot of the SCRs was oriented the same way for all SCRs in the simulations while they are randomly oriented in the sample, and the length of the simulated waveguide was 2 or 3.5 mm (depending on the case examined), which is significantly shorter than that of the experiment sample, due to time and memory constraints. The four cases, as shown in Fig. 1(c), as well as an intermediate case, are considered.

A. Case 1

In this case, the radiation propagates perpendicularly to the axis of the SCRs, the magnetic field is perpendicular to the plane of the SCRs, and the electric field has a component across the slot. Both fields will excite the magnetic resonance, which will contribute to confinement. Furthermore, as there is no wavevector component along the SCRs, spatial dispersion does not play a role. To characterize this case, three values for the core size, $d$, were used – 2, 3, and 4 mm – as the core size may affect the transmittance through the coupling efficiency and the number of modes guided.

The measured transmittance for the three core sizes are shown in Fig. 6, all showing qualitatively similar behavior. At frequencies below the magnetic resonance (164 GHz), low transmission is observed. At the magnetic resonance there is a peak in transmission, with transmission decreasing again for higher frequencies. This is most pronounced for the smallest core size. In addition, a dip in transmission is observed at 330 GHz.

![Figure 6: Measured transmittance of waveguides with various core sizes for Case 1. The resonance frequency is indicated by the solid line.](image)

The relatively high transmission between 160 GHz and 230 GHz can be explained by the refractive index and impedance of the SCR plates shown in Fig. 5. In terms of the refractive index, guidance can be attributed to total internal reflection when the refractive index of the SCR plates is less than 1. In terms of impedance, the strong mismatch between the SCR plates and the air core yields strong reflection.

![Figure 7: (a) Transmittance of waveguides with various core sizes, comparing experimental and simulation results. (b) Color density plot for the simulated magnetic field frequency of 164 GHz, showing Hz in the waveguide. In the simulation, Perfect Match Layers were added outside the SCR plates. A close up of one resonator showing (c) Hz, and (d) Ex.](image)

Figure 6 shows a transmission dip around 330 GHz in the case of $d = 2$ mm and $d = 3$ mm. This is not due to a magnetic resonance, but instead is associated with guidance out of the core and through the cladding, through the gaps between adjacent metal cylinders in the SCR array, as shown in Fig. 8(a). This phenomenon, termed slit resonance, has been reported for metallic gratings [31]. The slit resonance frequency depends on the width of the slits, which in the present case relates to the spacing of the SCR fibers. From Fig.
6 we can see that the slit resonance becomes weaker as the core size increases, to the point where it is not observed for \( d = 4 \text{ mm} \): less power is coupled to the slits between the cylinders for the larger core, as for a larger core the relative strength of the field at the edge of the core is lower.

To confirm that this transmission dip is a slit resonance, we compared simulations of the transmittance of the SCR waveguide to identical waveguides with a closed cylinder, and with the outer dielectric layer removed. The results are shown in Fig. 8(b). The closed cylinders not having a magnetic resonance, the main transmission peak is absent for these. The SCR waveguide and the waveguide with closed cylinders have almost the same slit resonance frequency. Removal of the dielectric outside the metal ring (dashed blue curve in Fig. 8(b)) shifts the transmission dip because it changes the refractive index of the material between adjacent cylinders, confirming the dip is due to slit resonances. The simulated slit resonance frequency is higher (370 GHz) than we observe in the experiment (330GHz, shown in Fig. 6), and the experimental resonances are broader – we attribute this to variation in diameter and spacing of the SCR fiber array in the experiment. Furthermore, Fig. 8(c) shows the electric field in the x direction at (370 GHz) and far from (420 GHz) the slit resonance frequency. At the slit resonance frequency, there is strong field confinement between adjacent metal cylinders, with a dipole field characteristic of the slit resonance. Far from the slit resonance there is no field confined between cylinders.

**FIG. 8.** (a) Schematic of transmission through the cladding between adjacent slotted cylinders, which gives rise to the slit resonance, depending on the width of the slit (diameter of the SCR fibers). (b) Simulated fields at the slit resonance (370 GHz) and away from the slit resonance (420 GHz). (c) Simulated transmittance for the waveguide when the cladding is composed of SCRs, closed cylinders, and closed cylinders without the external dielectric coating.

**B. Case 2**

In this case, the radiation propagates parallel to the axis of the SCRs. The electric field is in the plane of the SCRs and may excite the magnetic resonance for resonators that happen to have the slot oriented appropriately. Although the magnetic field is nominally in the plane of the SCRs, due to a tilting of the wavevector (see inset to Fig. 9), there will be a small component of the magnetic field perpendicular to the plane of the resonators, which will also excite the magnetic resonance. Hence, the radiation in this case may be guided by magnetic confinement, as in Case 1, but the excitation of the magnetic resonance will be much weaker. The tilting of the wavevector will differ for different core sizes as the mode’s effective index will change, and this will affect the component of the wavevector along the SCRs. Hence, spatial dispersion will be observed. A larger core will produce a larger effective index for the fundamental mode, and hence a larger wavevector component along the SCRs (larger angle in Fig. 4). The resonance is thus expected to be closer to the 164 GHz normal incidence value for smaller core sizes and at increasingly higher frequency for larger core sizes.

Figure 9 shows the experimental transmittance for \( d = 2 \text{ mm} \) and \( 4 \text{ mm} \). Distinctive dips in transmission are observed around 190 GHz and 210 GHz respectively. These are attributed to the loss associated with the magnetic resonance, previously observed just below 160 GHz in Case 1. The remaining features observed in Case 1, such as the increase in transmission just above the resonance frequency are less pronounced here, due to the overall weaker excitation of the resonance. The increased frequency of the transmission dip and the shift to even higher frequency for the larger core size is consistent with the effect of spatial dispersion.

**FIG. 9.** Transmittance of waveguides with various core sizes for Case 2. Inset shows that a magnetic field component along the SCRs arises from a tilt in the wavevector.

**C. Case 3**

In this case, the radiation propagates parallel to the axis of the SCRs, and nominally both the electric and magnetic fields are perpendicular to the axis of the SCRs. The magnetic field does not excite the magnetic resonance. Due the tilting of the wavevector, there will be a small component of the electric field parallel to the SCRs (as shown in the inset in Fig. 10); this component will see a wire array and experience a metallic reflection for frequencies below the effective plasma frequency. The magnetic resonance can also be excited by the electric field which is across the slot for appropriately oriented SCRs – and the resonance will shift depending on core oriented SCRs – and the resonance will shift depending on core size due to spatial dispersion, as was the case for Case 2.
Figure 10 shows the transmittance of the waveguide for Case 3 with $d = 3$ mm. The waveguide has high transmission at low frequencies due to the metallic reflection of the electric field component parallel to the SCRs, as expected. A dip in transmittance appears due to the loss associated with the magnetic resonance excited by the electric field, at 220GHz, consistent with spatial dispersion.

![Experimental transmittance of the waveguide under Case 3. Inset shows that an electric field component along the SCRs arises from a tilt in the wavevector.](image1)

**FIG. 10:** Experimental transmittance of the waveguide under Case 3. Inset shows that an electric field component along the SCRs arises from a tilt in the wavevector.

**D. Case 4**

In this final case the radiation propagates perpendicularly to the SCRs. The magnetic field is in the plane of the SCRs, while the electric field is parallel to the SCRs so that neither can excite the SCR’s resonance. The electric field being parallel to the SCR, sees a plasmonic medium. As a result, metallic reflection is expected for frequencies below the effective plasma frequency, estimated above to be in the range of 920 GHz (from experimental measurements, Fig. 3) to 1.18 THz, using Eq. (1).

The transmittance was investigated for $d = 2$mm, and is shown in Fig. 11. As expected, higher transmission is observed for lower frequencies, with an abrupt drop in transmission at 1.15 THz. This Case was also modelled and the numerical results are also shown in Fig. 12. It is noted that the length of the waveguide in the simulation is only 2 mm, compared to the experimental length of 4.6 cm, and the simulation results do not include coupling losses, explaining the higher transmission observed in simulations.

![Transmittance of SCR plate for various incident angles, lower panel: Transmittance of the waveguide for various incident angles](image2)

**FIG. 11:** Experiment and simulation results for transmittance of the waveguide for Case 4 with $d = 2$mm.

E. Transition from Case 1 to Case 3

In a final study, the waveguide was arranged as for Case 1 with $d = 3$ mm and then rotated to the geometry of Case 3, i.e. the waveguide was rotated in the $xz$ plane in Fig. 1(a). This increases the component of the wavevector along the SCRs, increasing the magnetic resonance frequency due to spatial dispersion. It also decreases the component of the magnetic field perpendicular to the plane of the SCRs, meaning the excitation of the magnetic resonance by the magnetic field is weaker, whilst metallic reflection and excitation of the SCR resonance through the electric field occur as discussed for Case 3.

![Upper panel: Transmittance of SCR plate for various incident angles, lower panel: Transmittance of the waveguide for various incident angles](image3)

**FIG. 12:** Upper panel: Transmittance of SCR plate for various incident angles, lower panel: Transmittance of the waveguide for various incident angles

Figure 12, lower panel, shows the transmission through the waveguide as it was rotated, with $0^\circ$ corresponding to Case 1 and $90^\circ$ to Case 3. As observed for Case 1 (Fig. 6), a low transmission below the resonance frequency is followed by increased transmission at the resonance frequency. This transition moves to increasing frequency as the angle is increased, due to spatial dispersion, and these features become less pronounced, with only the loss feature remaining prominent due to the weaker excitation of the resonance, as observed in Case 2 and Case 3 (Figs. 9 and 10). The upper panel in Fig. 12 shows the transmission for the corresponding angles...
through the SCR array as in the spatial dispersion measurement of Fig. 4, so that the upward frequency shift may be compared.

90° rotation corresponding to Case 3, shown in Fig. 10, exhibits a yet higher shift to the resonance frequency.

V. SUMMARY

In conclusion, we experimentally and numerically characterized the transmission properties of a waveguide with an air-core and SCR plates as the cladding. Four configurations consisting of two propagation directions and two polarizations were studied.

Confinement of radiation in the air core was achieved by an electric response (metallic reflection) or a magnetic response, depending on the polarization of the radiation. Excitation of the magnetic resonance was achieved by a magnetic field parallel to the slotted cylinder resonators or by an electric field across the slot. Retrieved values of the refractive index show that around the magnetic resonance, the refractive index of the SCR plate is below 1, achieving guidance by total internal reflection within a hollow core.

Other interesting phenomena were also observed in the experiments. The SCR plate could strongly absorb terahertz radiation when the slit resonance occurs at 370 GHz. The consequences of spatial dispersion were observed under several conditions.

By changing the waveguide and/or polarization configuration we have been able to show various guiding mechanisms and regimes, tuning the position of the effective resonance and accessing guidance for different frequency ranges. While our main motivation was in exploring and understanding the physics behind the various regimes, this waveguide could provide function-tunable devices based on a single waveguide.

The structure of this waveguide is simple and mass fabrication is possible by using fiber drawing techniques. The interesting phenomena shown in the experiment indicate that the waveguide could have many promising applications in manipulating and filtering radiation.

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REFERENCES
