2D titanium carbide (MXene) for wireless communication

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With the development of the Internet of Things (IoT), the demand for thin and wearable electronic devices is growing quickly. The essential part of the IoT is communication between devices, which requires radio-frequency (RF) antennas. Metals are widely used for antennas; however, their bulkiness limits the fabrication of thin, lightweight, and flexible antennas. Recently, nanomaterials such as graphene, carbon nanotubes, and conductive polymers came into play. However, poor conductivity limits their use. We show RF devices for wireless communication based on metallic two-dimensional (2D) titanium carbide (MXene) prepared by a single-step spray coating. We fabricated a ~100-nm-thick translucent MXene antenna with a reflection coefficient of less than −10 dB. By increasing the antenna thickness to 8 µm, we achieved a reflection coefficient of −65 dB. We also fabricated a 1-µm-thick MXene RF identification device tag reaching a reading distance of 8 m at 860 MHz. Our finding shows that 2D titanium carbide MXene operates below the skin depth of copper or other metals as well as offers an opportunity to produce transparent antennas. Being the most conductive, as well as water-dispersible, among solution-processed 2D materials, MXenes open new avenues for manufacturing various classes of RF and other portable, flexible, and wearable electronic devices.

INTRODUCTION

Fueled by societal demand for devices that enable active, efficient, and integrated lifestyles, there is an ever-increasing need for portable and wearable electronics. With the rising development of the Internet of Things (IoT), those devices need a concealed integration of radio communication electronics (I) without sacrificing light weight and transportability. Therefore, the development of new routes of antenna fabrication is needed.

Common antennas use metals, such as silver, copper, or aluminum, as conductors. The use of metals is dictated by the need of high electrical conductivity for transmitting and receiving radio waves. However, the performance of thin metal antennas is limited by an intrinsic property called the skin depth, which is the thickness of the material where the electrical current responsible for the radio-frequency (RF) radiation is effectively flowing. In a bulk metal, more than 98% of the electrical current flows within a layer with a thickness of about four times of the skin depth from the surface (2).

The skin depth is frequency-dependent. For example, the skin depth of copper at the Wi-Fi or Bluetooth frequency (2.4 GHz) is 1.33 µm. Silver and aluminum have skin depths of 1.29 and 1.67 µm, respectively, which means that the thickness of these metal antennas should be at least ~5 µm for these applications to ensure a sufficient space for the electrical current to flow. In wearable and transparent devices, skin depth becomes a limiting factor, making thin antenna fabrication challenging. Other approaches, such as metallic yarn manufacturing (3), have been used. However, fabricating flexible, conformal, easy to handle, thin metal antennas is not an easy task.

To overcome these challenges, alternative materials such as conductive polymers or nanomaterials have been explored in the field of RF wireless communication device manufacturing. These materials have to be easily processable, so they can be coated into conductive films. For example, one of the common conductive polymers, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, was used to produce an optically transparent dipole antenna (4) having a gain of −4 dB, translating into 40% of transmitted power loss from the antenna. To improve the performance, composites with metal nanoparticles have been used. For example, 150-µm-thick stretchable electropositive fiber mats dip-coated by silver nanoparticles, with an electrical conductivity of ~5400 S/cm, were used to design flexible antennas (5). In the past decade, carbon-based nanomaterials have been extensively investigated in wireless communication applications. For example, carbon onions (6), carbon nanotubes (CNTs) (7,8), and graphene (9, 10) were used for the fabrication of antennas. Other two-dimensional (2D) materials, such as the metallic 1T phase of MoS2, were explored for fabrication of electronic devices operating in the gigahertz region (11). Despite promising experimental results of the use of 1D and 2D nanomaterials, the theoretical understanding of these devices remains limited. Specifically, all these nanomaterials perform at thicknesses below their predicted skin depth (see more details in the Supplementary Materials). For example, the conductivity of a graphene antenna was reported (12) to be 43 S/cm, and at an operating frequency of 10 GHz, the skin depth is calculated to be 77 µm. However, the reported graphene antenna was only 7.7 µm thick (12), and the reported gain reached 1.9 dB. This could possibly be explained by different mechanisms of wave propagation in 2D and 1D materials. In particular, the behavior of waves propagating through nanomaterials at the radio frequencies has been investigated (13, 14), but a full theoretical insight has not yet been reached.

Despite the promising performances of carbon nanomaterials and other 2D materials in the RF communication application, their electrical conductivity is still relatively low, and several steps, such as incorporating conductive additives, are required to achieve a reasonable RF performance (6–12). Among all solution-processed 2D materials known to date, the as-deposited 2D titanium carbide MXene films have shown to have high electrical conductivities of up to 5000 to 10,000 S/cm, which exceed those of other solution-processed 2D materials (15) and makes them the best candidate for antenna fabrication. The 2D titanium carbide with a formula of Ti3C2 is a member of a family of 2D transition metal carbides and nitrides, known as MXenes, with a formula of M2n+1Xn, where M is an early transition metal (such as Ti, V, Nb, and Mo) and X is carbon or nitrogen. Chemically

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synchronously charged with stable colloidal solution in various organic and non-organic solvents. Various methods including rolling (19), spraying (20), spin coating, drop casting (21), and printing, which makes MXene a great candidate for RF applications.

In 2016, a thin film of Ti$_3$C$_2$ and its composites have shown electromagnetic interference (EMI) shielding capabilities comparable to metals and outperforming other nanomaterials of similar thicknesses (22). Here, we report on the first flexible MXene dipole antennas with thicknesses from 62 nm to 8 µm operating in the Wi-Fi and Bluetooth frequency bands, as well as an ultrahigh-frequency RF identification device (RFID) tag. In addition, by preparing a MXene transmission line (TL), we have studied radio wave propagation through MXene films.

RESULTS AND DISCUSSION

The MXene synthesis procedure can be found in the Supplementary Materials. Briefly, Ti$_3$C$_2$ MXene was synthesized from Ti$_3$AlC$_2$ by etching its aluminum layers in fluoride-containing acidic solutions (23). When selective etching was completed, we washed the MXene powder in deionized (DI) water to raise the acidic pH to neutral. Further delamination occurred due to intercalation of Li$^+$ ions between the layers and resulted in a stable aqueous colloidal solution of Ti$_3$C$_2$ flakes (Fig. 1A) suitable for film fabrication via filtration, spraying, printing, or spin coating. In our study, we focus on producing thin films by spraying technique for film thicknesses below ~1.4 µm and vacuum-assisted filtration for thicknesses above 1 µm (Fig. 1A).

We used an air spray gun to spray MXene aqueous colloidal solution (MXene ink; Fig. 1A). To show the diversity of possible substrates, we sprayed the MXene ink on relatively smooth polyethylene terephthalate (PET) sheets and on rough substrates such as cellulose paper (Fig. S1 and table S1; detailed procedure can be found in the Supplementary Materials). To improve adhesion to the surface, we used oxygen plasma treatment on the substrate before the deposition. The commercially available PET substrate that we used had a surface roughness at the nanometer scale (fig. S2). The scattering parameter S11 at the input port was recorded using a vector network analyzer (VNA) to quantify the reflection loss of the antenna, which indicates the amount of power reflected at the port with respect to what is delivered as input (2). The amount of power that is not reflected goes into the antenna and is partly radiated as energy or is lost in the material as ohmic losses. The return loss shows the 50-ohm impedance matching condition, as shown in Fig. 2B and fig. S4 for Ti$_3$C$_2$ MXene antennas with thicknesses from 62 nm to 8 µm. MXene antennas show good impedance matching. Figure 2B shows Ti$_3$C$_2$ antennas with thicknesses from 114 nm to 8 µm, and the peak return loss results from ~12 to ~65 dB, respectively. Peak return losses lower than ~10 dB are commonly considered satisfactory impedance matching. MXene return loss is increasing with decreasing of the antenna thickness (table S2). This trend could partially correspond to the decrease of conductivity, but mostly, it is related to the change of resistance with length, which decreases more markedly in the thinner films because of manual spraying, as shown in Fig. 1E.

To fabricate MXene films with thicknesses larger than ~1 µm, we vacuum-filtered the MXene colloidal solution—the same solution that we used for spray coating. To compare the MXene films made via different fabrication routes (sprayed or filtered), we used XRD (Fig. 1D). Because MXene synthesis involves aqueous solutions, water molecules are present between the individual 2D flakes. To remove the interlayer water and increase MXene film conductivity, we treated them at 150°C for 24 hours under vacuum. The XRD pattern for the as-sprayed samples on the PET substrate has a broad (002) peak around 5.2°, showing an interlayer spacing of ~17 Å for the MXene film. After thermal treatment, the peak shifts to 6.1° and sharpens, which indicates improved flake alignment and a smaller interlayer spacing of ~14.5 Å. However, the as-filtered films have even smaller interlayer spacing of ~12.9 Å, and thermal treatment further removes the water in between the 2D MXene sheets and leads to an interlayer spacing of ~10.6 Å. Hence, filtered films have less confined water in the structure and higher conductivities, as discussed below.

A common parameter for characterization of materials for RF circuits is sheet resistance. Figure 1E shows the dependence of the sheet resistance on thickness, measured using a linear four-point probe resistance measurement. Conductivity of the filtered freestanding film with a thickness of 8 µm was 8000 S/cm. MXene film thickness measurements are described in the Supplementary Materials. The thicknesses of ~600 nm and less were determined using an ultraviolet-visible (UV-vis) spectrometer from the calibration curve (20) available for the spraying method. The procedure is also described in the Supplementary Materials. Sheet resistance of the thickest sprayed film (1.4 µm thick) reached 0.77 ± 0.08 ohms/sq (Fig. 1E). The thinnest sprayed film exhibited 49% of transmittance of light at 550 nm and a sheet resistance of 47 ± 8 ohms/sq. The 49% transmittance corresponds to a thickness of around 62 nm. As shown in Fig. 1E, the sheet resistance increases significantly for thicknesses ≤100 nm, which is probably caused by interrupted flake connections due to the limitations of manual spray coating method.

We have prepared and tested three different kinds of MXene devices to explore three different ways for achieving RF communication and demonstrating relevant MXene properties: (i) a dipole antenna for exploring radiation properties, (ii) a TL for wave propagation properties, and (iii) an RFID tag to study the backscattering.

A Ti$_3$C$_2$ straight dipole antenna is easy to manufacture, making it ideal for the first MXene antenna study. Half-wave dipole antennas are commonly used for broadcasting, cellular phones, and wireless communication due to their omnidirectional properties. We designed the MXene dipole at 2.4 GHz, which is widely used for Wi-Fi and Bluetooth applications. The total length of the dipole is about 62 mm (Fig. 2A), which corresponds to half wavelength at a working frequency of 2.4 GHz. To quantify the antenna performance, we studied return loss and the radiation properties of the antenna.

The scattering parameter S11 at the input port was recorded using a vector network analyzer (VNA) to quantify the return loss of the antenna, which indicates the amount of power reflected at the port with respect to what is delivered as input (2). The amount of power that is not reflected goes into the antenna and is partly radiated as energy or is lost in the material as ohmic losses. The return loss shows the 50-ohm impedance matching condition, as shown in Fig. 2B and fig. S4 for Ti$_3$C$_2$ MXene antennas with thicknesses from 62 nm to 8 µm. MXene antennas show good impedance matching. Figure 2B shows Ti$_3$C$_2$ antennas with thicknesses from 114 nm to 8 µm, and the peak return loss results from ~12 to ~65 dB, respectively. Peak return losses lower than ~10 dB are commonly considered satisfactory impedance matching. MXene return loss is increasing with decreasing of the antenna thickness (table S2). This trend could partially correspond to the decrease of conductivity, but mostly, it is related to the change of resistance with length, which decreases more markedly in the thinner films because of manual spraying, as shown in Fig. 1E.

For the 8-µm-thick MXene antenna, we measured a reflection coefficient of approximately ~65 dB, which, to our knowledge, outperforms
all the nanomaterial antennas of comparable thickness measured to date, including silver inks and paste. Even with a 1.4-μm-thick MXene antenna made by spraying MXene water-based colloidal solution, we were able to obtain a reflection coefficient of approximately −36 dB, outperforming the 7-μm-thick printed graphene (12), laminated graphene (10), or printed silver ink (24) (table S2). Figure S5 summarizes the results presented in table S2 and shows that Ti₃C₂ MXene dipole antennas exhibit the highest performance-to-thickness ratio. The increase in return loss at very low thicknesses (that is, smaller than 100 nm) could be explained by the lack of film uniformity due to the PET substrate roughness and the manual spray deposition method. In addition, we fabricated dipole antennas with different MXene materials, Ti₃C₂ and Mo₂TiC₂ with ~1-μm-thick filtered films. Both Ti₃C₂ and Mo₂TiC₂ had reflection coefficients lower than −10 dB, showing the possibility of making antennas using different kinds of MXenes (fig. S6A). While they did not perform as good as Ti₃C₂ MXene antennas, the search for the best MXene for antenna applications should continue.

We also performed electrodynamic simulations (CST Microwave Studio), and a good match throughout all the thicknesses was observed (Fig. 2B). CST Microwave Studio is a tool for 3D EM simulations of high-frequency components, which solves Maxwell equations by resorting to specific meshing schemes, both in the time domain and in the frequency domain (25). The dipole antennas are simulated through a thin surface impedance layer with resistivity given by the sheet resistance. We considered a 100-μm-thick layer of lossy substrate as the PET sheet. A discrete 50-ohm port is used as a source.

To quantify the impedance matching at the operating frequency and different thicknesses, the VSWR was calculated (Fig. 2C) using the formula

$$\text{VSWR} = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

VSWR is the ratio between the peak amplitude and the minimum amplitude of the standing wave that arises from any mismatching condition at the antenna input, which causes input power to be reflected back. A VSWR equal to 1 means that there is no standing wave (S₁₁ = −∞) and that the antenna is ideally matched (3, 26). As shown in Fig. 2C, the VSWR is less than 2 for MXene antennas with various thicknesses despite the fact that the surface resistance increases significantly with thicknesses below 100 nm. As a reference, a VSWR equal to 2 means that 11% of the power is reflected.

We also fabricated dipole antennas using commercially available metal foils (aluminum and copper) with different thicknesses (at the
micrometers level) and compared their performance with Ti$_3$C$_2$ MXene antennas (Fig. 2C and fig. S6). Both copper and aluminum antennas showed similar VSWRs at significantly higher thicknesses (Fig. 2C). This shows that Ti$_3$C$_2$ MXene is able to match the impedance at very low antenna thicknesses, which can be easily fabricated by one-step spray coating. However, the antenna might not radiate all the power it receives. Part of this power is lost by ohmic losses, and these will affect the overall efficiency of the antenna. Thus, radiation measurements in the anechoic chamber are required.

We tested MXene dipole antennas in the anechoic chamber, as shown in Fig. 2D. The anechoic chamber is a shielded room that minimizes reflections from the floors, walls, and ceiling to create a "quiet zone" around the antenna under test. The radiation pattern was recorded at an operating frequency of 2.4 GHz by varying the elevation angles. Figure 2E shows the radiation pattern of an 8-μm-thick dipole antenna with typical dipole radiative behavior, where the maximum radiation occurs in the perpendicular direction and nulls are in the longitudinal direction. All radiation patterns can be found in figs. S6B and S7.

To quantify the amount of power effectively radiated from the MXene dipole antenna, the realized gain was calculated with the reference to a standard commercial copper dipole antenna (TDK DP 2400). The gain comparison technique was used (27). The 1.4-μm-thick MXene antenna showed a gain of 1.7 dB. The gain values of all the MXene antennas presented in Fig. 2F decrease when thickness is reduced. We performed electromagnetic simulations for the MXene antenna gains for the similar thicknesses showing a good match with the data set (Fig. 2F). Simulation shows also that, at a thickness of 8 μm, the MXene antenna exhibits a maximum gain of 2.11 dB, which is converging to the maximum gain of an ideal half-wavelength dipole antenna (2.15 dB). Despite the fact that the predicted skin depth for MXene at a frequency of 2.4 GHz would be 10 μm, Ti$_3$C$_2$ MXene antennas were able to radiate effectively and provide very good matching to the reference impedance at thicknesses below 1 μm.

So far, we have shown MXene antenna performance. In addition, to quantify the losses in a conductive material itself, we investigated the electromagnetic wave propagation in a MXene TL. TLs are basic blocks for a variety of RF devices, such as impedance matching networks, resonators, and filters (2), and are designed to carry the RF signal from one point to another with a minimum loss of energy due to the material losses. TLs also serve as a feeding line for antennas in a circuit. There are various types of TLs. We have selected a coplanar waveguide (CPW) as shown in Fig. 3A, in which the signal is carried by a central conductor, and the two side conductors work as grounding. In our TLs, the central conductor is 1.7 mm wide, and it is spaced 0.5 mm apart from the grounding conductor lines. The total length of the line is 50 mm (Fig. 3A). To characterize a TL, two-port measurements with VNA are required. The recorded parameters were reflection ($S_{11}$) and transmission...
The attenuation rate can be generalized by normalizing it with respect to the total length. In this way, it becomes a figure of merit that is independent of the actual sample length, and it characterizes material performance in the microwave region.

We fabricated Ti$_3$C$_2$ MXene TLs with the same MXene films as we used for the dipole antennas, from film thicknesses of 62 nm to 8 µm. Figure 3B shows attenuation increases with the decrease of the TL film thicknesses. For the TLs of various thicknesses, simulations were carried out, showing a good match with the experimental results. In Fig. 3C, the attenuations at 1 GHz versus sheet resistance are shown together with the simulated data. Reflection ($S_{11}$), transmission ($S_{21}$), and attenuation of all the sprayed Ti$_3$C$_2$ MXene TLs as well as Al and Cu TLs can be found in fig. S8. To check the flexibility of the MXene TLs, we performed the measurements in bending and normal mode (Fig. 3D). No changes were observed, which makes MXene a great candidate for flexible and wearable wireless communication devices. However, it was previously shown that, with increasing bending cycles, the sheet resistance is increasing by 14% (20). This could possibly be improved by using the spin-coating method with more uniformly distributed flakes.

To compare MXene antennas with other nanomaterials, we plotted the attenuations of different antenna materials from the literature in Fig. 3E. These results show that a 1.4-µm-thick Ti$_3$C$_2$ MXene film has about 50 times less losses at 1 GHz than a 7.7-µm-thick graphene-printed film (12) and 300 times less than a silver ink–printed antenna (24), which makes Ti$_3$C$_2$ MXene a great candidate for manufacturing ultrathin RF devices.

We also designed and fabricated MXene RFID tags. The geometry and working principal mechanism of RFID antenna is shown in Fig. 4A. Generally, these antennas consist of a radiating part and an impedance matching segment. The matching segment is typically a loop because it serves to match the input impedance of the RFID chip, which is highly capacitive. The matching condition is achieved by enforcing maximum power transfer to ensure both maximum power to the chip and maximum backscattering. In this case, we have used NXP UCODE 7 (see details in fig. S9). In Fig. 4B, the downlink reading distances of three different Ti$_3$C$_2$ MXene RFID tags are shown, where each antenna has slightly different loop sizes (fig. S9), thus enabling matching conditions at different frequencies. All the MXene RFID tags exhibit a reading range above 6 m at peak (Fig. 4B), reaching almost 8 m when maximum matching is achieved.

Using MXene for antenna applications, one should know that few-atom-thick single flakes of Ti$_3$C$_2$ MXene (~1 nm thick) are stable in inert atmosphere (Ar) but slowly degrade in air due to oxidation. Lipatov et al. (28) showed that, although Ti$_3$C$_2$ single-layer flake’s conductivity decays in air, Ti$_3$C$_2$ remains highly conductive even after exposure to air for 70 hours. Stacks of single-layer Ti$_3$C$_2$ flakes, such as filtered or sprayed MXene films, are stable in air. It was shown (15) that a filtered MXene film of 1.4 µm thickness is only about 50 times less losses at 1 GHz than a 7.7-µm-thick graphene-printed film (12) and 300 times less than a silver ink–printed antenna (24), which makes Ti$_3$C$_2$ MXene a great candidate for manufacturing ultrathin RF devices.
film of Ti$_3$C$_2$ is stable in air upon storage for 30 days, which can be explained by its compact stacked morphology that protects the inner nanosheets from interacting with humid air. To completely eliminate MXene oxidation, it is possible to laminate final devises or incorporate them inside the protective polymer matrices.

Here, we reported the first RF MXene devices for wireless communication. An 8-μm-thick antenna made from a filmstrip of 2D titanium carbide MXene has a reflection coefficient of $-65$ dB at 2.4 GHz. We showed the possibility of MXene antenna fabrication by a one-step spray processing from MXene water-based colloidal solution (ink). A 1.4-μm-thick MXene antenna made by spraying showed a gain of up to 1.7 dB. Even at a significantly lower antenna thickness of 62 nm, where we achieve transparency, the antenna is still able to perform, reaching a gain of $-7$ dB. The decrease in performance could be possibly explained by the limitation of the spray coating and has yet to be optimized. MXene antennas were able to achieve impedance matching in the wide range of thicknesses from 62 nm to 8 μm. Losses caused by the material were determined by assembling a MXene CPW TL. Attenuation of a m-thick MXene film was 50 times lower than that of a 7.7-μm-thick printed antenna.

**MATERIALS AND METHODS**

**MXene synthesis**

The material used in this study was synthesized by selective etching of Al atomic layers from Ti$_3$AlC$_2$. One gram of Ti$_3$AlC$_2$ powder (particle size, <44 μm; Carbon-Ukraine) was gradually added to a 10 mL solution of 6 mL of 12 M hydrochloric acid, 3 mL of 49% hydrofluoric acid (Sigma-Aldrich), and 1 mL of deionized water (25). The mixture was kept in an ice bath for 10 min and then stirred for 24 hours at room temperature. After etching, the mixture was washed five times by centrifugation at 2000 rpm for 1 min, and the collected supernatant was used for spraying. Ti$_3$C and Mo$_2$TiC$_2$ films were made as described elsewhere (22).

**Ti$_3$C$_2$ spraying on PET**

A smooth PET sheet (TruLam, thickness 4 mil, 100 μm) was used as a substrate for spraying due to their transparency and flexibility. Before deposition, PET substrates were cleaned by sonication in 5% Hellmanex III (Sigma-Aldrich) detergent solution for 3 min, followed by sonication in DI water and 190-proof ethanol. Sonication in all cases was limited to 3 min. After drying with compressed air, substrates were cleaned with oxygen plasma to remove residual contamination and make the surface more hydrophilic. Plasma cleaning (Tergeo Plus Plasma Cleaner, PIE Scientific) was done with 4 sccm (standard cubic centimeters per minute) O$_2$ gas flow, 50 W for 5 min. The chamber was purged with Ar gas after. PET surface was not ideally smooth, as can be seen from the atomic force microscopy (AFM) image in fig. S1. The roughness of cleaned PET reached 23 nm, which could be an obstacle for deposition of very thin MXene films. Ti$_3$C$_2$ dispersion in water was loaded into a spray gun. Constant flow of air from a hot gun above the PET substrate provided sufficiently fast drying, making the process easy, fast, and straightforward.

**Measuring sheet resistance**

Sheet resistance was measured by four-point probe measurements (Jandel ResTest). Each value was measured at least 10 times, and the average value was presented. SD was calculated as an error.

**Determining thickness**

Because of the limitations of conventional methods of measuring the thickness of thin films, an indirect method based on Beer’s law was used. It was shown (20) that the relationship between MXene sprayed film absorption and thickness is linear. Having the relationship between thickness and absorption, one can calculate the thickness. We have measured UV-vis absorption spectra of our films (fig. S3). A blank PET sheet was used as a reference. For thicknesses of the sprayed opaque films, the thickness was calculated by measuring the sheet resistance of the sprayed films and comparing it to the sheet resistance of the freestanding film of known thickness.

**Scanning electron microscopy**

The SEM was performed with a Zeiss Supra 50VP instrument at an acceleration voltage of 5 kV in InLens mode.
Atomic force microscopy
Bruker MultiMode 8 with a Si tip (Budget Sensors Tap300Al-G; $f_0 = 300$ kHz, $k = 40$ N/m) was used in a standard tapping mode in air.

UV-vis spectroscopy
A UV-vis spectrophotometer (Thermo Scientific Evolution 201) was used. A MXene film sprayed on the PET substrate was placed in a slide holder. A clean PET sheet was used as a reference for the measurements. Spectra were collected in both modes—transmittance and absorbance. To calculate MXene film thickness, the absorbance value at 550 nm was used.

X-ray diffraction
Rigaku XRD Smartlab was used to collect XRD patterns. The x-ray wavelength used was 1.5406 Å (Cu Kα) at 40 kV and 44 mA, with a step scan of 0.02°, a 2θ range of 3° to 70°, and a step time of 0.5 s, 10 mm × 10 mm window slit.

Electrodynamic simulations
Electrodynamic simulations were carried out using the commercial software CST Microwave Studio. The software solves Maxwell equations by resorting to the finite integration technique (FIT) in time domain and to a finite element method (FEM) in the frequency domain.

**SUPPLEMENTARY MATERIALS**
Supplemental material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/9/eaau0920/DC1

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