Broadband surface-wave transformation cloak

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Guiding surface electromagnetic waves around disorder without disturbing the wave amplitude or phase is in great demand for modern photonic and plasmonic devices, but is fundamentally difficult to realize because light momentum must be conserved in a scattering event. A partial realization has been achieved by exploiting topological electromagnetic surface states, but this approach is limited to narrow-band light transmission and subject to phase disturbances in the presence of disorder. Recent advances in transformation optics apply principles of general relativity to curve the space for light, allowing one to match the momentum and phase of light around any disorder as if that disorder were not there. This feature has been exploited in the development of invisibility cloaks. An ideal invisibility cloak, however, would require the phase velocity of light being guided around the cloaked object to exceed the vacuum speed of light—a feat potentially achievable only over an extremely narrow band. In this work, we theoretically and experimentally show that the bottlenecks encountered in previous studies can be overcome. We introduce a class of cloaks capable of remarkable broadband surface electromagnetic waves guidance around ultrasharp corners and bumps with no perceptible changes in amplitude and phase. These cloaks consist of specifically designed nonmagnetic metamaterials and achieve nearly ideal transmission efficiency over a broadband frequency range from 0^+ to 6 GHz. This work provides strong support for the application of transformation optics to plasmonic circuits and could pave the way toward high-performance, large-scale integrated photonic circuits.

transformation optics | surface wave | invisibility cloaks | broadband

O ne of the main limitations in plasmonic circuitry and devices (1, 2) that use surface electromagnetic waves (surface plasmons at optical frequencies) as information and energy carriers is the inability to perfectly guide surface electromagnetic waves around unavoidable disorders, such as sharp corners. Although near-perfect transmission around sharp corners in electronic circuits is routine, it is fundamentally difficult to realize with surface waves, because surface waves suffer from scattering loss when encountering sharp corners or other irregular disorders.

Scattering-free guidance of surface waves around sharp corners has been shown only in topological electromagnetic surface states (3–7). It has been developed in analogy with electronic chiral edge states in quantum Hall systems (8) and topological insulators (9, 10). To force the waves to circumvent disorders, the studies cited above typically require the use of photonic crystals with substantial magnetic responses (11). The use of magnetic metamaterials limits these realizations to a narrow-microwave frequency band. The use of conventional nonmagnetic photonic materials, however, could allow for scalability to the optical regime with broad bandwidth.

The difficulty in sharp bending is the dramatic momentum mismatch of surface electromagnetic waves before and after passing the sharp corner in an extremely compact space. Transformation optics (12, 13) allow for the design of inhomogeneous metamaterials that control light by effectively warping the electromagnetic space

analogously to the way that gravity curves space in general relativity. Because the concept of momentum stems essentially from space homogeneity (14), an effectively curved electromagnetic space provides a method to match wave momenta by compensating for the asymmetry of spatial translation around sharp corners. Surface electromagnetic waves can be, thereby, deceived that they are still propagating along a flat surface without any corners.

In the past few years, transformation optics has been used to develop invisibility cloaks to hide objects from free-space propagating electromagnetic waves (15–23). An ideal invisibility cloak is a fundamentally narrow band, because it would require the phase velocity of light being guided around the "cloaked object" to exceed the vacuum speed of light (13, 15, 24). However, surface electromagnetic waves are essentially slow waves, with bending that will not cause superluminal propagation in the majority of situations, but all of the potential applications of transformation optics in surface electromagnetic waves (25–29) so far are still theoretical. Most theoretical designs only deal with objects with relatively smooth surfaces or finite bending radii (25, 26). Refs. 28 and 29 proposed alternative surface wave-bending approaches; however, in general, scattering will occur when an ultrasharp bending with zero radius is desired. Therefore, if a similar approach of sharp bending could be realized for surface waves, many unique conceivable applications would become feasible: not only waveguides for sharp right-angle corners (3) but also, carpet cloaks that can hide irregular bumps on the metal–dielectric interface (26), super plasmonic resonators with extremely high Q values (30), etc.

Here, we present experimental demonstration of broadband sharp bending of surface electromagnetic waves with almost

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Significance

Guiding surface electromagnetic waves around disorder without disturbing the wave amplitude or phase is in great demand for modern photonic and plasmonic devices. In this work, we introduce a class of cloaks capable of remarkable broadband surface electromagnetic waves guidance around ultrasharp corners and bumps with no perceptible changes in amplitude and phase. This work provides strong support for the application of transformation optics to plasmonic circuits and could pave the way for high-performance, large-scale integrated photonic circuits.

ideal transmission, which allows "invisibility cloaking" of disorders, such as ultrasharp corners and bumps for surface electromagnetic waves. The remarkable broadband guidance, lacking in previous scattering-free topological electromagnetic surface states and free-space invisibility cloaks, is because of two reasons. First, the slow-wave property of surface electromagnetic waves can overcome the bottleneck of free-space invisibility cloaks, because its phase velocity does not need to exceed the vacuum speed of light. Second, we adopt a fully nonmagnetic design with naturally accessible dielectric parameters, whereas magnetic responses were necessary to open the topological band gap for topological electromagnetic surface states.

We start with the demonstration of bending a surface electromagnetic wave across sharp right-angle corners at microwave frequencies—similar to the previous demonstration of bending a guided topological surface electromagnetic wave in a photonic crystal (3). We call the bending adaptor a "corner cloak," because it effectively hides a corner to the wave as if the corner did not exist. Because metals at microwave frequencies are perfect electric conductors that generally do not support surface electromagnetic waves, here we adopt the approach of geometrically induced or spoof surface plasmons (31) [i.e., we use a grooved metallic surface (referred to as a patterned metal in Figs. 1–3) to support surface electromagnetic waves in the microwave regime]. Fig. 1A shows the experimental setup: a U-shaped surface-wave waveguide (a metal base with periodic grooves on its surfaces; i.e., the patterned metal) with two right-angle zero-radius corners. Given the sizes of the cloaks, the more confined the surface waves on the dielectric–metal interface, the better the cloaking performance. To enhance the confinement, we load the grooves with ceramic material with permittivity $\varepsilon_{ceramic} = 21$. We use glass with permittivity $\varepsilon_b = 4.6$ as the surrounding background that is to be impedance-matched with the cloaks. More details can be found in Fig. S1 and SI Methods.

The two identical corner cloaks locate at the two corners. This structure that consists of the U-shaped waveguide and two corner cloaks can be thought of as if it were transformed from a straight waveguide without any corner. A corner cloak, when transformed back, corresponds to a triangular space on top of the dielectric–metal interface, which has an area that is purposely chosen to be the same as the corner cloak. This area preservation guarantees nonmagnetism in the cloak design for surface electromagnetic waves (more details are in Fig. S2 and SI Methods). The two identical corner cloaks require anisotropic constitutive parameters. For each cloak, the required principal permittivities in two orthogonal directions, ε_1 and ε_2, after the procedure of diagonalization, where only components in the xy plane are relevant, are $\varepsilon_1 = 10.7$ and $\varepsilon_2 = 2.0$. These cloaks were implemented with a metamaterial consisting of a stack of the following two materials with subwavelength thicknesses: a microwave dielectric ceramic with permittivity $\varepsilon_{ceramic} = 21$ (Wuxichaoying K-21; loss tangent: 1×10^{-4}; 1-mm thickness) and a polymer foam with permittivity $\varepsilon_{foam} = 1.1$ (Rohacell 71HF; loss tangent: 16×10^{-4}; 1.06-mm thickness). According to the standard formulas of effective medium theory, one can get

$$\begin{cases} \varepsilon_1 = r\varepsilon_{ceramic} + (1-r)\varepsilon_{foam} \\ \varepsilon_2 = \dfrac{\varepsilon_{ceramic}\varepsilon_{foam}}{\left[(1-r)\varepsilon_{ceramic} + r\varepsilon_{foam}\right]} \end{cases},$$

where the filling factor is given by $r = 0.485$. Fig. 1B shows the simulation of the transmission of surface electromagnetic waves when the corners are not cloaked by the corner cloaks; a dramatic scattering loss is evident. However, the transmission of surface electromagnetic waves across a sharp corner is perfect when both corners are cloaked by corner cloaks (Fig. 1C).

A fabricated model with two corner cloaks is shown in Fig. 1D. For comparison, we also fabricated a straight waveguide with
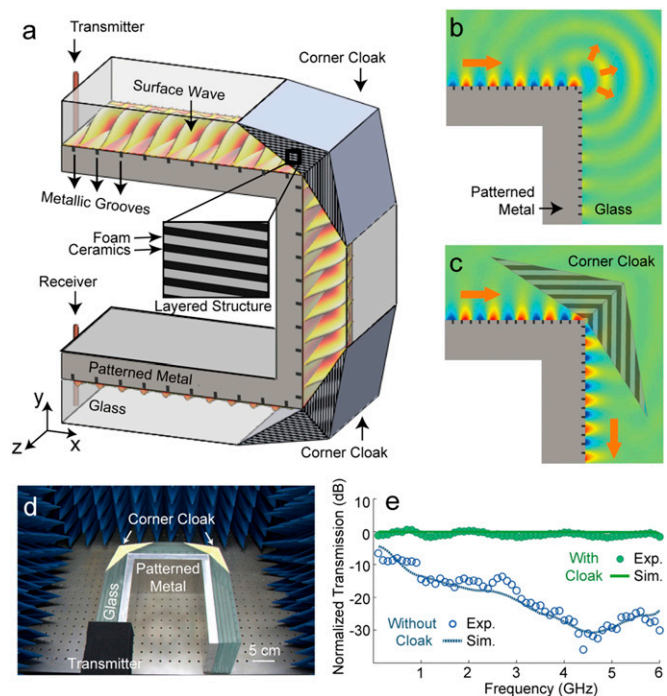

Fig. 1. Surface-wave bending around sharp corners. (A) A U-shaped surface-wave waveguide with grooves on its surface covered by glass is illuminated by a dipole antenna. The two sharp corners are covered by two corner cloaks (i.e., layered structures with subwavelength foam and ceramic materials). A second dipole antenna located at the output of the waveguide measures the transmission. (B) Simulation of a surface wave when it encounters a sharp corner that is not covered by a cloak. (C) Simulation of a surface wave when the sharp corner is cloaked by a corner cloak. (D) Photo of a fabricated model. The transmitter is shielded by the microwave absorber material. (E) Measured normalized transmission of surface waves through the waveguide. Exp., experimental data; Sim., simulation data.

similar grooves and the same total propagation distance. The transmission data measured on the U-shaped surface-wave waveguide from 0^+ (100 MHz) to 6 GHz without/with corner cloaks are normalized to the transmission data measured on the straight waveguide (Fig. 1E). Without corner cloaks, the transmission measured at the output of the U-shaped waveguide is close to zero, but when both sharp corners are hidden by the corner cloaks, the transmission is almost unity. The experimental result shows near-perfect cloaking of two right-angle zero-radius corners for surface electromagnetic waves in a broad bandwidth from 0^+ to 6 GHz (i.e., with a fractional bandwidth of 200%).

Next, we show a surface-wave carpet cloak used to cover an ultrasharp bump on a flat metal–dielectric interface. Fig. 2A shows our experimental setup. Like in the realization of the corner cloaks, we used a metal base with grooves to support surface electromagnetic waves. A sharp bump on the flat surface acts as an obstacle able to block the propagation of surface electromagnetic waves. The carpet cloak that can hide this sharp bump was designed with a similar transformation optics approach (more details can be found in Fig. S3 and SI Methods). The numerical simulation for the real structure in the presence of a sharp bump is shown in Fig. 2 B and C: without a carpet cloak, most of the wave energy is scattered into the background medium near the apex of the bump; when the carpet cloak is put on top of the bump, however, the electromagnetic surface waves can be smoothly guided around the bump and returned to their original path as if the bump was not there. A fabricated model with a carpet cloak implemented with the same metamaterial used in the corner cloaks is shown in Fig. 2D. The measured transmissions, normalized to the
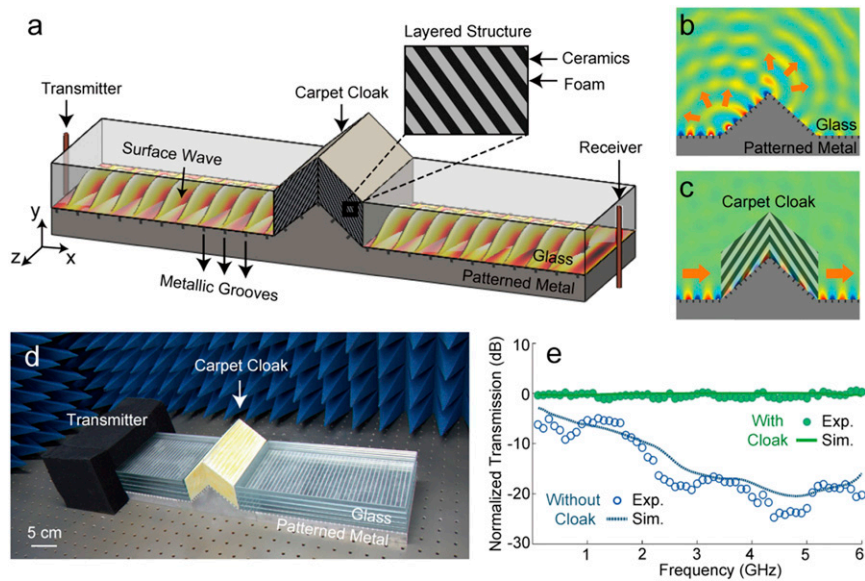
Fig. 2. Surface-wave carpet cloaking. (*A*) A straight surface-wave waveguide with a sharp bump is illuminated by a dipole antenna. The surface of the metal base is grooved similarly as that in Fig. 1*A*. The sharp bump is covered by a carpet cloak (i.e., a layered structure with subwavelength foam and ceramic materials). A second dipole antenna located at the output of the waveguide measures the transmission. (*B*) Simulation of a surface wave when it encounters the sharp bump without a carpet cloak. (*C*) Simulation of a surface wave when the sharp bump is cloaked by the carpet cloak. (*D*) Photo of a fabricated model. The transmitter is shielded by the microwave absorber material. (*E*) Measured normalized transmission of surface waves through the waveguide. Exp., experimental data; Sim., simulation data.

transmission through a straight waveguide without the bump, are shown in Fig. 2*E*. For the setup without a cloak, the normalized transmission is close to zero, indicating that the propagation of surface electromagnetic waves has been blocked by the bump. For the case with a carpet cloak, the normalized transmission approaches unity, showing near-perfect cloaking of a sharp bump for surface electromagnetic waves in a broad bandwidth from 0^+ to 6 GHz.

A striking feature, absent in topological electromagnetic surface states, is that, when the surface waves are perfectly guided by the cloaks, the phase is preserved. We used a pulsed signal to show this behavior. Fig. 3 shows the dynamic propagation of a pulse through the cloaks, which was obtained with the commercial software COMSOL Multiphysics. A point source at port 1 excites a Gaussian-shaped pulse (bandwidth: 0^+–6 GHz; center frequency: 3 GHz) at 0 ns. The magnetic
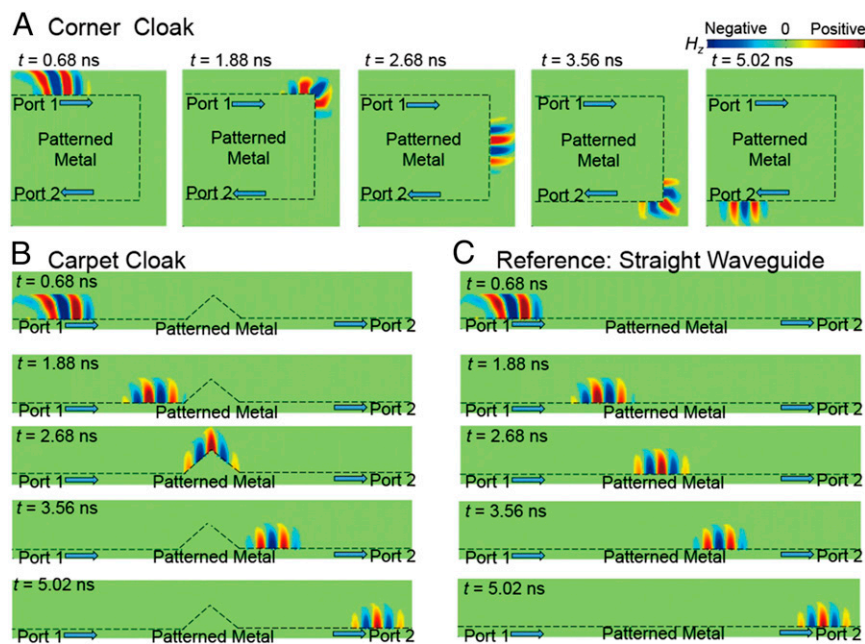

Fig. 3. A Gaussian-shaped pulse propagates on the patterned metal. A point source (port 1) generates the pulse at 0 ns. The bandwidth of the pulse is 6 GHz, and the center frequency is 3 GHz. The magnetic field distributions for three cases [(*A*) the corner cloaks, (*B*) the carpet cloak, and (*C*) the straight waveguide reference] are plotted to show the propagation of the pulse at five equivalent temporal sampling points.
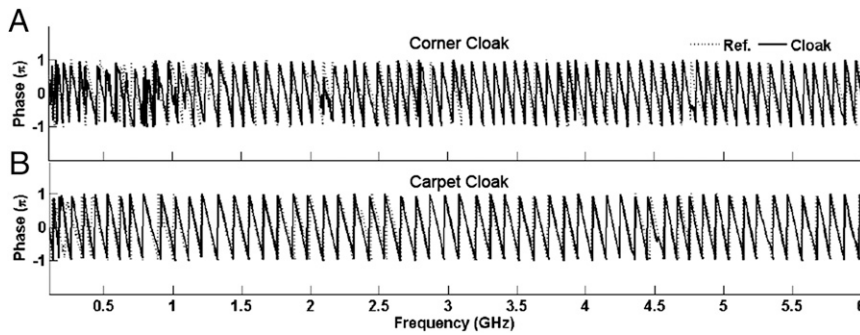
Fig. 4. Phase measurements. (*A*) The corner cloaks. (*B*) The carpet cloak. The phases with the straight waveguide are plotted for reference. In both cases, the phase curves almost coincide with their references over the frequency band from 0^+ to 6 GHz.

field distributions are plotted to show the propagation of the pulse on the patterned metal for the setup with the corner cloaks (Fig. 3*A*), the carpet cloak (Fig. 3*B*), and a straight waveguide as a reference (Fig. 3*C*). For the realization with corner cloaks, the signal reaches the first and second sharp corners at 1.88 and 3.56 ns, respectively. At both sharp corners, the pulse signal is perfectly guided by the corner cloak, and at last, it leaves the patterned metal from port 2. In the case of the carpet cloak, the pulse reaches the bump at 2.68 ns, and it is guided smoothly across the bump by the carpet cloak without any loss. The pulse reaches the same positions as in the straight waveguide, with no relative delay, indicating that the phase is well-preserved in a broad bandwidth by the cloaks. Movies S1 and S2 show more details of the propagating pulse. Fig. 4 shows the measured phase for the corner cloak (Fig. 4*A*) and carpet cloak (Fig. 4*B*). The curves almost coincide with their references over the frequency band from 0^+ to 6 GHz, confirming that the phase of the surface wave is well-preserved by the cloaks.

The above results show scattering-free guidance of surface electromagnetic waves around large disorders, with both wave energy and phase undisturbed in a 200% broad-frequency band.

Switching from free-space electromagnetic waves to surface electromagnetic waves, transformation cloaks can find immediate applications without any fundamental limitations. The fully nonmagnetic design makes it feasible to further extend to higher frequencies and/or conventional surface waves. Our work, thereby, paves the way for the next generation of photonic and plasmonic devices, allowing for flexible design without concern in disorders.

1. Raether H (1988) *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Springer, New York).
2. Ozbay E (2006) Plasmonics: Merging photonics and electronics at nanoscale dimensions. *Science* 311(5758):189–193.
3. Wang Z, Chong Y, Joannopoulos JD, Soljačić M (2009) Observation of unidirectional backscattering-immune topological electromagnetic states. *Nature* 461(7265):772–775.
4. Lu L, Joannopoulos JD, Soljacic M (2014) Topological photonics. *Nat Photonics* 8(11):821–829.
5. Khanikaev AB, et al. (2013) Photonic topological insulators. *Nat Mater* 12(3):233–239.
6. Chen W-J, et al. (2014) Experimental realization of photonic topological insulator in a uniaxial metacrystal waveguide. *Nat Commun* 5:5782.
7. Fang K, Yu Z, Fan S (2012) Realizing effective magnetic field for photons by controlling the phase of dynamic modulation. *Nat Photonics* 6(11):782–787.
8. Klitzing KV (1986) The quantized Hall effect. *Rev Mod Phys* 58(3):519–531.
9. Hasan MZ, Kane CL (2010) Colloquium: Topological insulators. *Rev Mod Phys* 82(4):3045–3067.
10. Qi XL, Zhang SC (2011) Topological insulators and superconductors. *Rev Mod Phys* 83(4):1057–1110.
11. Wang Z, Chong YD, Joannopoulos JD, Soljačić M (2008) Reflection-free one-way edge modes in a gyromagnetic photonic crystal. *Phys Rev Lett* 100(1):013905.
12. Leonhardt U (2006) Optical conformal mapping. *Science* 312(5781):1777–1780.
13. Pendry JB, Schurig D, Smith DR (2006) Controlling electromagnetic fields. *Science* 312(5781):1780–1782.
14. Landau LD, Lifshitz EM (1969) *Mechanics* (Pergamon, Oxford), 2nd Ed.
15. Schurig D, et al. (2006) Metamaterial electromagnetic cloak at microwave frequencies. *Science* 314(5801):977–980.
16. Liu R, et al. (2009) Broadband ground-plane cloak. *Science* 323(5912):366–369.
17. Valentine J, Li J, Zentgraf T, Bartal G, Zhang X (2009) An optical cloak made of dielectrics. *Nat Mater* 8(7):568–571.
18. Gabrielli LH, Cardenas J, Poitras CB, Lipson M (2009) Silicon nanostructure cloak operating at optical frequencies. *Nat Photonics* 3(8):461–463.
19. Ergin T, Stenger N, Brenner P, Pendry JB, Wegener M (2010) Three-dimensional invisibility cloak at optical wavelengths. *Science* 328(5976):337–339.
20. Ma HF, Cui TJ (2010) Three-dimensional broadband ground-plane cloak made of metamaterials. *Nat Commun* 1:21.
21. Zhang B, Luo Y, Liu X, Barbastathis G (2011) Macroscopic invisibility cloak for visible light. *Phys Rev Lett* 106(3):033901.
22. Chen X, et al. (2011) Macroscopic invisibility cloaking of visible light. *Nat Commun* 2:176.
23. Landy N, Smith DR (2013) A full-parameter unidirectional metamaterial cloak for microwaves. *Nat Mater* 12(1):25–28.
24. Chen H, et al. (2013) Ray-optics cloaking devices for large objects in incoherent natural light. *Nat Commun* 4:2652.
25. Burkay D, Teixeira FL (2008) Metamaterial blueprints for reflectionless waveguide bends. *IEEE Microw Wirel Compon Lett* 18(4):233–235.
26. Liu Y, Zentgraf T, Bartal G, Zhang X (2010) Transformational plasmon optics. *Nano Lett* 10(6):1991–1997.
27. Zhang J, Xiao S, Wubs M, Mortensen NA (2011) Surface plasmon wave adapter designed with transformation optics. *ACS Nano* 5(6):4359–4364.
28. Mitchell-Thomas RC, McManus TM, Quevedo-Teruel O, Horsley SAR, Hao Y (2013) Perfect surface wave cloaks. *Phys Rev Lett* 111(21):213901.
29. Patel AM, Grbic A (2014) Transformation electromagnetics devices based on printed-circuit tensor impedance surfaces. *IEEE Trans Microw Theory Tech* 62(5):1102–1111.
30. Xu H, Wang X, Yu T, Sun H, Zhang B (2012) Radiation-suppressed plasmonic open resonators designed by nonmagnetic transformation optics. *Sci Rep* 2:784.
31. Pendry JB, Martín-Moreno L, Garcia-Vidal FJ (2004) Mimicking surface plasmons with structured surfaces. *Science* 305(5685):847–848.

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