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Global Evolutionary Optimized Metasurface for Broad-angle Multisource Invisibility Cloaking

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As a new and advanced form of cloaking technology, metasurface cloaks have significant potential for widespread use in various fields owing to their excellent ultrathin and low-loss characteristics. Because of the principle of phase compensation based on incident direction, a metasurface cloak can operate only at a single specific angle (range). To be useful in real application scenarios, a cloak must be able to simultaneously handle multiple wide-angle detection waves. Various attempts have been made; however, currently, cloaks only work for a single detection source or are effective against incoming waves from a small incidence range. The design of a universal metasurface cloak that can flexibly respond to any number of sources at arbitrary incident angles remains a formidable challenge. Here, we present a global-evolution-optimization strategy for multisource and broad-angle meta-cloaks, which is based on a tunable metasurface to manipulate incoming waves at any angle over a wide range and is driven by an evolutionary game algorithm to satisfy the requirements for the cloaking of multiple simultaneous broad-angle incident sources. In experiments and simulations, the meta-cloak exhibited an impressive ability to render target objects invisible to both single and multiple incident waves at arbitrary angles, highly resembling background fields. This feasible cloaking strategy, which can be extended to any number of incident sources, provides an example of multisource wideband broad-angle scenario cloaking application.

Introduction

A long-cherished dream of mankind, hiding from detection using an invisibility cloak, has become a possibility thanks to rapid advances in metasurfaces. A metasurface is a sub-wavelength two-dimensional structure and its extreme thinness allows it to completely guide electromagnetic (EM) wave propagation [1–7]. A metasurface cloak covering an object can reduce the scattered field and restore the original electric field distribution of the propagated waves to present the illusion that the object is nonexistent [8–11]. According to the generalized Snell's law [12,13], passive
metasurfaces, which are favored owing to their fixed physical structures, can only provide a single-phase gradient and are highly sensitive to the incoming wave direction and frequency. Thus, passive meta-cloaks perform remarkably well with a static background, that is, for a constant incidence angle and frequency [14–17], but are constrained by the varying EM environment. Instead of the unalterable gradient of passive metasurfaces, active metasurfaces with integrated tunable electronics (e.g., PIN and varactor diodes) provide alterable phase gradients to adapt to more incidence angles and frequencies [18–21]. However, limited by the adjustable range of variable parameters and unstable response to large angles, existing active meta-cloaks mainly work at small incidence angles. Moreover, existing metasurface cloaks work only for a single incident direction. Thus, an invisibility cloak that can simultaneously act on large incident angles for multiple detection beams is urgently required, albeit challenging.

Multisource incidence increases the requirements for metasurface cloaks, transforming the one-to-one direct mode to a one-to-many nonlinear problem [22–24]. Metasurfaces are typically designed for specific incidence angles. This presents diverse and undesirable response characteristics for other incidences. In particular, for different incidences at the same frequency, the scattering fields of incoming waves at the metasurface interfere with each other [25–27]. Compared to the direct inference of metasurfaces from a single source [28–30], the case of multisource incidence requires the involvement of a counterintuitive design of optimization algorithms [31–33]. For multiple sources, particularly at a single frequency, the performance of the metasurface causes confliction and makes the sources difficult to separate, resulting in a game situation in which it is difficult to reach the optimal solution among multiple cloaking targets simultaneously. The optimization of one objective comes at the expense of the degradation of the other, resulting in the disappearance of a unique optimal solution [34–36]. Multiple sources must be compromised to achieve the most optimal solution. A suitable algorithm that can consider the global optimal solution of a multisource game is the key to realizing multisource cloaking.

In this work, we propose a tunable-metasurface-assisted strategy for broad-angle multisource cloaking driven by a global evolutionary optimization algorithm, and experimentally confirm that it can intelligently and flexibly respond to one or more incident sources at any angle (Fig. 1a). To implement the one-to-many concept, it is necessary to introduce nonlinear parameters such as phase permutation. The evolutionary-game-algorithm (EGA) herein is used to solve the nonlinear parameter arrangement problem of cloaking under multiple simultaneous incidence sources with arbitrary angles. Game theory emphasizes biodiversity and ensures the possibility of the global optimization of parameter solving. The abrupt phase changes caused by the tunable metasurfaces were controlled by feeding different direct current bias voltages to the varactor diodes. We demonstrate the broad-angle meta-cloak performance under single and double incident sources in any direction by simulation and experiment and prove that our meta-cloak is efficient and robust to two simultaneous incident waves. At any incidence angle, the cloaking capability in the three same-frequency sources and two broadband sources was verified by theory and simulation, respectively. The invisibility cloak can ideally restore the far-field distribution in accordance with the background field for single- and multiple-broadband and wide-angle incoming waves. Our cloaking strategy, which is easy to expand to broadband multi-angle and takes far-field recovery as the goal, facilitates the practical application of cloaking technology, granting radar and communication systems protection in demanding detection environments.
Fig. 1 Schematic of multisource broad-angle tunable meta-cloak. a In the general case, the meta-cloak is applied to any number of simultaneous incident sources. b Scattering far field caused by two sources of any direction and frequency, separately and simultaneously incident on cloaked and bare bump

Results

Working principle and evolutionary-game-algorithm optimization approach

In the case of simultaneous multisource incidence, the metasurface must simultaneously and separately compensate for the abrupt phase changes caused by the bump to multiple sources. Therefore, the metasurface falls into a contradictory situation in which multiple abrupt phases must be compensated for simultaneously. Here, we introduce a new metasurface design degree of freedom, phase permutation, to solve this nonlinear problem. For a given target, particularly for nonlinear problems, optimization algorithms can always find an optimal answer hidden in a phase arrangement that cannot be deduced directly [37–41]. Inspired by natural biological evolution, the EGA is a mature global optimization method with high robustness and wide applicability. The addition of game theory greatly preserves biodiversity and contributes to global optimization. It provides a coding scheme for the entire parameter space of the problem rather than directly dealing
with specific parameters. Instead of searching for a single initial point, the algorithm searches for a set of initial points. In contrast to the regular unit arrangement that can be inferred directly, evolutionary optimization algorithms constantly search for the best phase permutation (usually irregular) to meet the objective of hiding from multiple simultaneous detection waves. For the current one-to-many dilemma, the EGA simulates the natural evolution process and efficiently obtains an optimal solution regardless of the number of incident sources. Undoubtedly, utilizing the EGA to obtain the global optimal phase arrangement for broad-angle multisource cloaking occupies the preferred position. Here, the goal of the cloaking strategy is to recover the far field of the object; that is, to make the scattering caused by the presence of the object undetectable.

Without loss of generality, we consider the cloaking example to be a PEC bump whose arbitrary boundary is defined as \( h(x, y) \). The two-dimensional plane was divided into multiple grids of \( D \times D \) mm, as large as the metasurface unit. Considering the height difference caused by the bump, as shown in Fig. 1b, the plane wave reaching the bump can be expressed as

\[
P^{mn} = A e^{jk_y(x \sin \theta \cos \phi + y \sin \theta \sin \phi + z \cos \phi)}
\]  

where \( x = mD - \frac{D}{2}, y = nD - \frac{D}{2}, z = h(x, y) \). \( \theta \) and \( \phi \) represent the azimuth and pitch angles of the incident wave. Given the experimental environment and the accuracy of the analysis, under the illumination of an open-ended waveguide antenna, the far-field radiation pattern \( E(\theta, \phi) \) of the metasurface covering the bump (Fig. 2a) can be expressed as the superposition of the radiation fields from each metasurface element [42–44]:

\[
E(\theta, \phi) = \sum_{m=1}^{M} \sum_{n=1}^{N} P^{mn} \times f^{mn}(\theta, \phi)
\]  

where \( f^{mn}(\theta, \phi) \) is the radiation field from the \( mn \)-th element with a period of \( D \) mm. \( A^{mn} \) and \( \phi^{mn} \) represent the incident amplitude and phase due to the source illuminating onto the element, respectively. \( z^{mn} \) is determined by the bump boundary conditions corresponding to the \( mn \)-th element. Taking two sources incident simultaneously as an example, the far-field distribution is defined as

\[
E(i) = E_p(i) + E_q(i)
\]  

Specifically, \( E \) is the section of the 3D far-field pattern with \( \phi = 90^\circ \). \( i \) represents the index of the discrete samples on the computed beam pattern \( E \). The total far field is obtained by the superposition of two single far fields in complex form in Figs. 2b and c (see the simulation details of the two sources incident simultaneously in Supplementary Note 1). The fitness function of the EGA describes the error between the objective and optimization results [44] as follows:

\[
F = W_1 \times F_u + W_2 \times F_a
\]  

where \( W_1 \) and \( W_2 \) are the weight factors. \( F_u \) represents the error of the computed far field \( E \) that is greater than the desired upper mask \( E_u \), denoted as

\[
F_a = \sum_{i=1}^{N} (E(i) - E_u(i))^2
\]
and $F_i$ is the error of $E_i$ less than the desired lower mask $E_i$, and is denoted as

$$F_i = \sum_{i=1}^{N} (E_i - E_{i1})^2$$  \hspace{1cm} (6)$$

As shown in Fig. 2d, the upper mask is very close to the target far field to depress the side lobe. The lower and upper masks maintain a 3 dB beamwidth. The optimization objective of the EGA needs to better meet the requirements of the upper mask; therefore, $W_1$ and $W_2$ were set to 2 and 1, respectively. As desired, the far field obtained by optimization is highly similar to that of the target (Fig. 2e), even the simulation results in Fig. 2f. For illustrative purposes, the similarity between the target and far field obtained by the EGA-optimized distribution was evaluated using the Pearson correlation coefficient:

$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{A_i - \mu_A}{\sigma_A} \right) \left( \frac{B_i - \mu_B}{\sigma_B} \right)$$  \hspace{1cm} (7)$$

where $\mu$ and $\sigma$ are the mean and standard deviation of curves A and B, respectively. $\rho$ between 0.8–1 indicates a strong correlation, between the scattered field obtained by EGA optimization and the target far field.

Fig. 2 Radiation pattern of multiple sources with the same frequency. a Schematics of the proposed tunable meta-cloaks, which can reconstruct the wavefront of the bump as that of a flat mirror. b Full-wave simulation results of a single oblique plane wave incident on PEC plane. c A simulation example proves that the simultaneous incidence of two plane waves is equivalent to the far-field superposition of a single plane wave at the same frequency. d To reconstruct the target far field as closely as possible, the upper and lower masks limit the main lobe and side lobe in the optimization process. e The optimization results of EGA accurately approximate the target far field, and the position of the main lobes coincide completely. f Example simulation of full-wave double source incidence with EGA optimization arrangement.

Meta-atom and metasurface design

The key to realizing an invisible metasurface cloak for detecting waves in any direction is the
design of a tunable meta-atom with a sufficient phase range. As shown in Fig. 3a, the meta-atom consists of a simple metal-dielectric-metal sandwich structure with a period of $0.37\lambda$. Meta-atoms are separated by a column of metal vias with a diameter of 0.4 mm and spacing of 0.4 mm [45]. Metal vias acting as metal walls reduce the coupling between elements. The top layer was composed of symmetrical metal patches, and slender metal wires were used for power supply (see the specific parameters of the unit in Supplementary Note 2). A varactor diode (SMV2019-079LF) acted as a phase-tuning device, bridging identical metal patches on the top layer. The varactor exhibited varying capacitances at different reverse bias voltages, thereby manipulating the phase response of the unit. To obtain the EM performance of the unit, numerical simulations were implemented using the commercial software CST Microwave Studio based on the equivalent RLC circuit of the varactor. As shown in Figs. 3b and c, at normal and oblique incidences of 5.5 GHz, the phase coverage is wide at approximately $315^\circ$ under different bias voltages with a stable amplitude. In addition, the meta-atom is insensitive to oblique angles and maintains a similar phase change and stable amplitude, facilitating the design of the phase permutation. Figures. 3d and e respectively illustrate the phase and amplitude characteristics of the units in the experiment. At 5.5 GHz, the EM characteristics of the units were in excellent agreement with the simulation results.

To validate the proposed multisource cloaking strategy, a metasurface-based cloak that supports dynamic broadband phase control was designed. It consists of $36 \times 20$ units with a size of $720 \text{ mm} \times 336 \text{ mm}$ ($12\lambda \times 5.6\lambda$) and was fabricated by standard printing circuit technology. The meta-atoms in each column share the same voltage and those in each row manipulate the EM waves in an arbitrary direction.

**Fig. 3 Angle-insensitive and high-reflectivity metasurface unit cell design.** a Schematic of the meta-atom with a period of 20 mm. b Simulated reflection phase variation of our meta-atom at different oblique incidence angles under the excitation of 5.5 GHz x-polarized waves. c At 5.5 GHz, the amplitude of the unit cell is barely affected by the direction of the incoming wave. d At normal incidence, the measured phase coverage at different frequencies is approximately $300^\circ$. e In the experiment, the reflectance of the unit was relatively high, which is consistent with the simulation results of working frequency.

**Demonstration of metasurface cloak**

As a demonstration, full-wave simulations of a triangular metasurface cloak with a tilt angle of $15^\circ$ were performed using CST Microwave Studio (see the simulation setup of the plane wave as ...
For conceptual clarity, plane waves were incident on the metasurface cloak and the background PEC plane, and the horn antenna was the feed source of the bare bump. They were all placed on a metal PEC plane with strong reflections. To reduce the simulation complexity, a row of metasurface units was applied to form an invisibility cloak covering a metal bump. With the frequency-domain solver and plane-wave excitations, the period boundary was used in the y-direction, and the open boundary was applied in the other directions to mimic the actual experimental conditions. In the far-field distribution obtained by single or multiple sources incident on the ground PEC plane and the metasurface cloak, the wave peak positions accurately corresponded to the mirror reflection angles in the incident directions (Fig. 4). In particular, the recovered scattering field was identical to the background field under multiple incident sources at both large and small oblique angles. The chaotic far field was excited by a bump that is unrelated to the background field. The exemplary match between the optimization results and the target far field indicates the flexibility and effectiveness of our multisource broad-angle cloaking strategy. In fact, the beam emitted by a horn antenna $33\lambda$ (corresponding to experimental distance) away from the bump does not consist of perfect plane waves, but spherical waves. It is worth mentioning that for the PEC ground and metasurface cloaks, whether the incident wave is an ideal plane wave or a spherical wave has little influence on the simulation results. However, for a bare bump, the spherical wavefront cannot perfectly identify the original angle between the triangular bump and the horizontal PEC plane, resulting in a different phenomenon from the ideal plane wave incident (see the simulation setup of a horn antenna as a feed in Supplementary Note 4).

**Fig. 4 Full-wave simulations of metasurface cloak under single and multiple oblique incidence sources.**

**a** With oblique incident plane waves as the feed, the space field restored by the meta-cloak covering the metal bump and the far-field distribution of the PEC plane and a bare bump are analyzed. **b** Far-field distribution of multiple high-angle oblique plane waves incident on the ground, cloaked bump, and bare bump.

**Experimental realization of broad-angle multisource cloaking**
To experimentally verify our metasurface cloak, we fabricated metasurface samples based on an F4B dielectric material with a dielectric constant of 2.65 and a loss tangent of 0.001. A photograph of the prototype (fabricated using conventional printed circuit board technology) loaded with varactor diodes is shown in Fig. 5a. Our multisource cloak consists of two identical metasurfaces tilted at $\alpha = 15^\circ$ to preserve some space for hiding. The power supply lines of each column were connected and each row was supplied independently. In the experiment, a metal bump was covered with the meta-cloak and placed on the PEC ground. The bump illustrates the capacity of the cloaking space, which is applicable for objects of any shape. A standard gain horn antenna operating in the 4–6 GHz frequency band was connected to one end of the vector network analyzer as the emission source, and the other end was connected to a double-ribbed horn antenna to receive the electric field intensity. We fixed the entire cloaking device and transmitter to a turntable and placed the receiving horn a few meters away. To clearly explain the cloak performance, all experiments were performed in a microwave anechoic chamber. The incident wave direction $\theta = 0^\circ$, $\phi = 0^\circ$ is defined as the transmitter incident vertically to the PEC ground. It is worth mentioning that the actual incidence angle for the metasurface cloak is $|\theta \pm \alpha|$. Considering the insensitivity of the element to the incidence angle, we substituted the phase at vertical incidence for the case at oblique incidence. As an example, Fig. 5b shows a comparison of the field distribution of the metasurface cloak and the background PEC plane incident by x-polarized waves in different directions. The far-field variation recovered by the cloak maintained an excellent similarity with the PEC background field. According to Pearson's correlation coefficient, the similarity of incident angles at $10^\circ$, $20^\circ$, and $-45^\circ$ was 0.9050, 0.8543, and 0.9115, respectively, indicating outstanding far-field recovery. As shown in Fig. 5b, the EM waves encounter the bare bump and cause significant scattering, resulting in a chaotic and irregular distribution of the far field. Moreover, for the EM waves at a large incidence angle ($-45^\circ$), the recovered far field shows good coincidence with the background far field. Figure 5c shows the far-field distribution of the EM waves incident on the metasurface cloak, PEC ground, and bare bump in polar coordinates. The scattered fields of the invisibility cloak and background PEC almost completely coincide, which is significantly different from that of the bare bump.
Fig. 5 Experimental results of wide-angle meta-cloak for single incident waves at a large direction angle. a Photograph of the microwave measurement setup. b Measured 2D scattering patterns for the cloaked bump, ground, and bare bump at 5.5 GHz. c Scattering patterns for the ground, cloaked bump, and bare bump in a polar coordinate system.

Next, we measured the electric field intensity under simultaneous incidence of two sources operating at 5.5 GHz. To minimize the error, two identical standard gain horns, as emitters, were placed 2 m away from the metasurface to approximate the plane wave incidence. The two horns were connected to an ultra-wideband power divider such that the two incident wave signals were coherent with no difference in amplitude, as shown in Fig. 6a. Figure 6b shows the different incidence directions of multiple sources. At the same frequency, the scattered fields of the two sources are superimposed to form the total field. We validated various incident directions, including $45^\circ$ and $30^\circ$ at large angles, $45^\circ$ and $-30^\circ$ with significant differences, and small incident angles ($-10^\circ$ and $20^\circ$). Figure 6c shows the far-field distribution variations of the bump covered by the metasurface cloak and PEC ground plane, with two clearly visible peaks (corresponding to two source incidences). In the measured experimental results, the positions of the peaks are the mirror reflection angles of the incident wave directions, demonstrating excellent multisource cloaking performance. In the presence of multiple sources, the reflected field of the bare bump
became distorted and disordered (Fig. 6c). The strongly scattered field revealed the geometrical shape of the bump. More specifically, in Fig. 6d, the cloaked bump overlaps almost exactly with the ground far field, creating a sharp contrast with the bare bump. According to the Pearson correlation coefficient, the similarity coefficients of the three groups of incidence directions were 0.9071, 0.9053, and 0.9042, which further confirmed the effectiveness of our multisource cloaking strategy.

Fig. 6 Proposed broad-angle multisource meta-cloak and its performance. a Experimental setup of double source incidence. b Schematic of double source incidence direction. c Measured 2D scattering patterns for the cloaked bump, ground, and bare bump at 5.5 GHz. d Scattering patterns for the ground, cloaked bump, and bare bump with dual-source illumination in a polar coordinate system.

Discussion
For a clear demonstration of the cloaking optimization strategy and the facilitation of practical implementation, we exhibit a relatively simplified broad-angle multisource meta-cloaking with several major simplifications that will not impair the generality of our proposed strategy. For a single detection wave, the meta-cloak can flexibly respond to incoming waves in any direction, even at ±45° oblique incidence. The EGA, assisted by game theory, exhausts all possibilities in the search space to find the optimal solution, demonstrating the power of phase combination [46,47]. A series of experiments proved that aided by the EGA, the meta-cloak copes with two incoming waves without stress. In the presence of three incident sources at any angle, the meta-cloak also shows a satisfactory cloaking effect, with a correlation coefficient of 0.91 between the background and cloaking far field in the full-wave simulation results of Supplementary Note 5. In Supplementary Note 6, the invisibility cloak eliminates the scattering caused by the bumps and blends into the background field at different frequencies. According to the experimental and simulation results, the proposed meta-cloak is suitable for any number of wideband incident sources. Facilitating a practical-oriented invisibility cloak capable of rendering objects invisible, even under any number of simultaneous detections, is highly desired.

The metasurface cloak driven by the optimization algorithm is suitable for multiple incoming broadband waves from any direction. The working frequency of a tunable metasurface is inherently limited by the capacitance range of the varactor diode and resonant structure [48,49]. As can be observed from the simulation and experimental results, the designed meta-atom has a phase coverage range of 315° within 5–6 GHz. Without loss of generality, two incident sources of 5 GHz and 5.5 GHz in any direction were arbitrarily selected to verify the effectiveness of the meta-cloak (see the full-wave simulation results of the dual-frequency dual-source incident waves in Supplementary Note 6). In the scattering patterns at 5 GHz and 5.5 GHz, we observed a lobe distribution consistent with the PEC, and the main lobe corresponded to the specular reflection angle of the incident waves, proving that meta-cloaks can also be applied to multiple broadband source scenarios. An active cloaking strategy powered by optimization algorithms uses an array of elementary sources to offset the scattered fields caused by the hidden objects, potentially realizing broadband cloaking on any number of sources. With appropriate electronic detection and feedback devices, cloaking systems can operate actively and stably without intervention [50–52]. The control system receives the incoming wave information from the radar direction estimator and sends commands to control the cloaking system, which is a completely adaptive process [19]. Multisource estimation of incoming wave information typically requires cumbersome hardware and time-consuming algorithms. In recent years, rapid, simple, and accurate multisource incoming-wave detection methods have emerged, laying the foundation for multisource cloaking to progress into adaptive and intelligent stages [25,26].

Methods

Full-wave simulation. In the simulation, a metasurface cloak covering a metal bump was placed on the PEC plane. To reduce the simulation time and difficulty, only one row of the metasurface model was established, and the boundary conditions were periodic in the y-direction and open in both the x- and z-directions. Ideally, for the incident source, the metasurface cloak-covered bump is similar to a PEC; therefore, the simulation results of the plane-wave incidence are not different from those obtained by horn irradiation. After propagating for some distance (about 33λ), the beam emitted by the horn is still a spherical wave. The spherical wave cannot distinguish the included
angle between the metal ground and the bump, thus causing scattering, which does not conform to the theoretical analysis under the incidence of plane waves. The simulated bump RCS directly used a full-size horn as the emission source, as shown in Fig. S4.

**Global optimization of multisource metasurface cloak.** The required phase arrangement of the multisource cloaking metasurface was optimized using MATLAB. Global optimization was performed on a server (Intel(R) Xeon(R) Gold 6226R CPU @2.90 GHz with 256GB RAM). It takes approximately 7h and 70 generations for the multisource meta-cloak to converge.

**Experimental set-up.** The incident horn and metasurface cloak were placed on a turntable, and the receiving horn was placed 6 m away at the same height. The metasurface was placed vertically on an acrylic shelf with holes dug at a fixed angle, a metal bump behind it, and finally on a metal background. The transmitting horn was placed on an arc at the center of the metasurface to ensure that the entire measured object could receive EM waves. The receiving horn was connected to one end of the vector network analyzer using a 4–6 GHz low noise amplifier. Voltage control of the metasurface was achieved using a self-designed voltage control board with a 64-port output. The control board can output continuously varying adjustable voltages of −19–0 V (see control circuit implementation in Supplementary Note 7).

**Data availability**

All data and methods used to evaluate the conclusions of this work are presented in the main text and Supplementary Information. All other relevant data are available from the authors upon request.

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**Author contributions**
B.Z. and H.S.C. conceived the idea. M.H. conducted the numerical simulations and carried out the experiment; X.F.L. and R.C.L. helped to validate the simulation and build the experimental platform. B.Z., L.S., R.R.Z., H.L. and M.H. analyzed the data and wrote the paper; B.Z., T.C. and H.S.C. shared their insights and supervised the project.

**Competing interests**
The authors declare no competing interests.

**Additional information**
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