Microwave Waveguide-Type Hyperbolic Metamaterials

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Hyperbolic metamaterials (HMs) supporting hyperbolic isofrequency curves (IFCs) provide unprecedented control on wave propagation and light-matter interaction. However, in the microwave regime, ultrahigh wave vectors and customizable permittivity tensors cannot be supported simultaneously by current common HMs. Based on the waveguide principle, low-loss waveguide-type HMs (WHMs) are suggested as a new geometry format of microwave HMs, flexibly mixing positive and negative components in their effective permittivity tensors. Then, a deeply subwavelength WHM cavity, confirming the existence of giant wave vectors, is demonstrated, whose transverse size has a potential to be reduced to three orders smaller than the working free-space wavelength. Such a WHM cavity is also demonstrated to follow the fascinating anomalous scaling law originating from the unique shape of hyperbolic IFCs. As a low-loss platform, WHMs are predicted to produce distinctive physical phenomena based on HMs and provide novel functional devices at low frequencies.

1. Introduction

Metamaterials are artificial materials engineered at the subwavelength scale. Hyperbolic metamaterials (HMs) are a special kind of metamaterials, possessing hyperbolic isofrequency curves (IFCs).[1,2] HMs have been used in many novel phenomena and applications. They have been used in subwavelength imaging, such as subdiffraction-limited focusing,[3] hyperlens,[4] and canali-

zation.[5] As large state density can be realized in a broadband, they have been used to enhance light-matter interaction, such as enhanced spontaneous emission[6,7] and near-field thermal transfer.[8,9] Due to the noncompact IFCs and strong anisotropy, they have been used to construct small anomalous-scale cavities,[10] slow-wave-based ultrabroadband absorbers,[11,12] large-wave-number waveguides,[13] special scatterers,[14,15] polarization controllers,[16] enhanced sensing,[17,18] and nonlinear optics.[19,20] In the optical range, HMs are traditionally constructed based on metal/dielectric multilayered structures or metal wire arrays in dielectric matrices, and large metal loss may degrade their functions. Natural HMs, such as hexagonal boron nitride, have also been explored recently,[21–23] which are little limited by finite unit periods compared with artificial HMs. In the microwave regime, considering that metal layers cannot be used to construct layered HMs because they are opaque, the arrays of metal wires embedded in background materials are commonly used to realize HMs.[24] In such an HM, the effective permittivity component along the wire axes can be negative, but almost infinite, and the components perpendicular to the metal wires are always positive and determined by the host permittivity. Thus, the attainable variation in the effective permittivity tensor is rather limited. Recently, HMs based on metal metasurfaces supporting guided modes have also been proposed by utilizing anisotropic unit cells.[25] However, as smaller resonant unit cells were hard to design with their method, large wave vectors are strongly limited by the nonlocal effect.[26] There is also another kind of microwave HMs made of magnetic natural materials, but the material loss is great, and the apparatus applying static magnetic field is usually cumbersome.[27,28]

Here, flat metal waveguides are suggested to act as building blocks for a new geometry format of microwave HMs. By adjusting the geometric parameters or the filling material, the effective permittivity of a metal waveguide can switch from positive to negative,[29,30] When subwavelength waveguide segments of negative effective permittivity and ones of positive effective permittivity are arranged alternately, a waveguide-type HM (WHM) similar to an optical layered HM is then formed. Due to ultrasmall periodicity and low material loss, giant wave vectors may be supported by some propagating modes inside WHMs. Unlike wire HMs, the permittivity tensor components of WHMs maintain full tunability. Especially, they can transit across zero, inducing the so-called topological transition.[6] This property makes WHMs possess more flexibility in modulating various electromagnetic behavior, including scattering, waveguiding, and localizing. Also, the structure format of WHMs is convenient to be integrated into microwave waveguide circuits.
2. Results and Discussion

2.1. Constructing WHMs

A waveguide, consisting of two metal plates sandwiching a dielectric plate of permittivity $\varepsilon_b$ and height $h$, is investigated. Under the TE$_{10}$ mode, the waveguide mode behaves like a plane wave propagating in an effective electric medium. As treating the metal as a perfect electric conductor (PEC), the effective relative permittivity can be simply deduced as

$$\varepsilon_{wg} = \varepsilon_b - \frac{\lambda_0^2}{4h^2}$$  \hspace{1cm} (1)

where $\lambda_0$ is the free-space wavelength. According to Equation (1), $\varepsilon_{wg}$ exhibits the Drude dispersion and switches its sign by adjusting $\varepsilon_b$ or $h$ appropriately.

Then, two types of subwavelength dielectric slices with thicknesses $d_1$ and $d_2$, respectively, are alternately arranged in a period of $p_x = d_1 + d_2$ along the $y$-direction between the top and bottom metal plates (Figure 1a), whose relative permittivities are $\varepsilon_{b1}$ and $\varepsilon_{b2}$, respectively. The field behavior is equivalent to that of a plane wave propagating in an electric anisotropic medium. With the effective medium theory (EMT), the effective relative permittivity tensor of the composite waveguide structure is found to be

$$\varepsilon_{whm,x} = \frac{\varepsilon_{wg1}d_1 + \varepsilon_{wg2}d_2}{d_1 + d_2}$$
$$\varepsilon_{whm,y} = \frac{d_1/\varepsilon_{wg1} + d_2/\varepsilon_{wg2}}{d_1 + d_2}$$ \hspace{1cm} (2)

The wave propagation behavior follows the dispersion equation

$$\frac{k_{x,whm}^2}{\varepsilon_{whm,y}} + \frac{k_{y,whm}^2}{\varepsilon_{whm,x}} = k_0^2$$ \hspace{1cm} (3)

where $k_0$ is the free-space wave number. When the two filling materials are two types of ceramics (barium tetratitanate of relative permittivity $\varepsilon_{b1} = 38.50$ with loss factor $\tan \delta_{b1} = 1.24 \times 10^{-4}$ and anorthite of relative permittivity $\varepsilon_{b2} = 5.5$ with $\tan \delta_{b2} = 1 \times 10^{-4}$), and $h = 60$ mm, the working frequency is around $f = 0.7$ GHz, and the effective relative permittivities corresponding to the two waveguide segments are $\varepsilon_{wg1} = 25.76 + 0.0049i$ and $\varepsilon_{wg2} = -7.24 + 0.00055i$ according to Equation (1) (time harmonic factor $\exp(-i\omega t)$ is assumed). By inserting the two values into Equation (2) with $d_1 = d_2 = 1$ mm, one has that $\varepsilon_{whm,x} = 9.26 + 0.0027i$ and $\varepsilon_{whm,y} = -20.13 + 0.0036i$. According to Equation (3), it is known that the IFC at $0.7$ GHz of the composite waveguide is hyperbolic; thus, a WHM is attained. The values of $\varepsilon_{whm,x}$ and $\varepsilon_{whm,y}$ can be varied in a large range by adjusting the parameters in Equation (2), including zero, infinite, and negative, which is an advantage of the WHM compared with wire HMs.

The above-mentioned investigation is made under the assumption that there only exists waveguide mode TE$_{10}$. An unwanted waveguide mode, TM$_{10}$, can exist simultaneously along the parallel-plate waveguide. To prevent the cross coupling from TE$_{10}$ to TM$_{10}$ due to interface scattering, additional thin metal wires are added on each slice interface to short-circuit the electric component of $E_z$ and quench waveguide mode TM$_{10}$.

Here, thin silver wires (conductivity $\sigma_{Ag} = 6.30 \times 10^7$ S m$^{-1}$) are distributed in a period of $p_x$ with width $d_x$, thickness $d_y$, and...
height $h$. The top and bottom metal plates are made of copper ($\sigma_{\text{Cu}} = 5.70 \times 10^7 \text{ S m}^{-1}$). Full-wave simulation is conducted by the eigenfrequency solver in the wave optics module of COMSOL. The mesh-element size within the metal wires is set below 5 $\mu m$ along the $x$- and $y$-directions, and below 1.5 mm along the $z$-direction. The solver is required to find the eigenfrequencies around 0.7 GHz by iteration, and then, we check the electrical field patterns to determine the correct eigenmodes. For a given Bloch vector of $k_x$ and $k_y$, a complex eigenfrequency, $f_{\text{eig}}$, can be found, and $\text{Re}(f_{\text{eig}})$ represents the working frequency, and $\text{Im}(f_{\text{eig}})$ the attenuated rate. When $p_x = 1$ mm, $d_x = 0.2$ mm, and $d_y = 0.02$ mm for the silver wires, the simulated IFC at $\text{Re}(f_{\text{eig}}) = 0.7$ GHz is shown in Figure 1b. The hyperbolic IFC, curved toward the $k_y$-direction, ends at the Bloch boundary of $\pi/p_y$. As the WHM is anisotropic, the total in-plane wave vector and the effective mode attenuation rate (or quality factor $Q_{\text{whm}}$) change with $k_x$. The former one is $k_{\text{tot}} = (k_x^2 + k_y^2)^{1/2}$, whereas the latter one can be calculated by $Q = -\text{Re}(f_{\text{eig}}) / 2\text{Im}(f_{\text{eig}})$ as a general definition.\(^{[31]}\) $k_{\text{tot}}$ and $Q_{\text{whm}}$ corresponding to Figure 1b are shown in Figure 1c. Maximum $k_{\text{tot}}$ is up to 120 $k_0$, whereas $Q_{\text{whm}}$ remains larger than 100.

If one further reduces $p_x$ and $p_y$, to weaken the nonlocal effect, larger wave vectors can be produced. With a set of optimized parameters ($p_x = p_y = 100$ $\mu m$, $d_x = 20$ $\mu m$, and $h = 54.2$ mm), the IFC at 0.7 GHz is shown in Figure 1d. The finite period of metal wire arrays may also limit the largest attainable wave vectors due to the nonlocal effect. The Bloch boundaries of $K_{\text{travg}} = \pi / p_y = \pi / p_x = 2141.5$ $k_0$ terminate the IFC, giving the maximum $k_{\text{tot}}$ of 3028.5 $k_0$. This giant wave vector over 3000 $k_0$ is realized with $Q_{\text{whm}}$ larger than 10 (see Figure 1e). WHMs provide an effective way to break the limit of natural materials and achieve giant effective refractive index ($n_{\text{whm}} = k_{\text{tot}} / k_0$) with relatively low dissipation.\(^{[32,33]}\) which can simply synthesize composite materials can possess the huge relative permittivities up to $10^6$, but work only at low frequencies below a few megahertz.\(^{[34]}\) In the gigahertz range, the relative permittivity of typical high-permittivity natural material is only around 100.\(^{[35]}\)

### 2.2. Hyperbolic IFCs in Broadband

The IFC behavior of the constructed WHMs at various frequencies can be qualitatively understood according to Equation (2). The WHM investigated in Figure 1b is taken as an example. When $f$ approaches the topological transition frequency around 0.533 GHz, as $\text{Re}(f_{\text{whm},x}) = 0$ and $\text{Re}(f_{\text{whm},y}) \rightarrow \infty$, the corresponding IFC should be rather flat, which can be used to realize the canalization effect.\(^{[19]}\) Above 0.533 GHz, the hyperbolic IFCs should open along the $k_x$-directions, because $\text{Re}(f_{\text{whm},x}) > 0$ and $\text{Re}(f_{\text{whm},y}) < 0$ (i.e., the central line of each continuous branch is along the $k_y$ axis). Below 0.533 GHz, the hyperbolic IFCs should open along the $\pm k_x$-directions, because $\text{Re}(f_{\text{whm},x}) < 0$ and $\text{Re}(f_{\text{whm},y}) > 0$. However, below 0.403 GHz, the WHM acts as an anisotropic plasmonic metal, and there are no bulk waveguide modes existing, because $\text{Re}(f_{\text{whm},x})$ and $\text{Re}(f_{\text{whm},y})$ are both negative. To verify the above-mentioned prediction, the IFCs at various frequencies are obtained by COMSOL (Figure 2). The simulated result is consistent with the qualitative analysis. By the above-mentioned investigation, it is demonstrated well that the constructed WHMs possess hyperbolic IFCs in a broadband, because they do not depend on localized resonance.

Note that we use EMT just to show that a constructed wave-type composite material behaves like an HM as a simple illustration. The accurate description of the propagating-mode behavior, considering the nonlocal effect and the influence of the added metal wires, is given in Figure 1b–d and 2 in terms of IFCs based on rigorous full-wave simulation.

### 2.3. Constructing WHM Cavities

The supported ultrahigh wave vectors enable one to construct subwavelength cavities based on WHMs. Such a cavity configuration is shown in Figure 3a, whose cross section is given in Figure 3b. It consists of five pairs of alternately arrayed anorthite slices and barium tetratitanate slices, bounded by two copper plates at the top and bottom. Each slice has a size of $10 \times 1 \times 60$ $\text{mm}^3$ (along the $x$-, $y$-, and $z$-directions, respectively).
and silver wires (0.2 × 0.02 × 60 mm³) are distributed on the two large surfaces of each barium tetratitanate slice with a period of \( p_x = 1 \text{ mm} \) along the \( x \)-direction. The total transverse size of the WHM cavity is small: The width along the \( x \)-direction is \( L_x = 10 \text{ mm} \), and the thickness along the \( y \)-direction is also \( L_y = 10 \text{ mm} \) (the thickness of the silver wires is ignored here). The top and bottom copper plates are very thin with a size of \( 10 \times 10 \times 0.2 \text{ mm}^3 \).

When some propagating mode, performing a round trip inside the WHM cavity, fulfills the Fabry–Pérot (FP) resonance condition, a cavity resonant mode can be formed. For analysis convenience, the WHM cavity is first assumed to have boundary conditions of PMC at \( \pm x \)- and \( \pm y \)-directions to eliminate the phase induced by the boundary reflection. A resonant mode is found to appear at 0.725 GHz by simulation. As shown by the electric mode pattern given in Figure 3c (normalized to some large value to saturate the illustrating color around the metal wires), there is one node in the electric field of \( E_x \) along the \( y \)-direction, and also in \( E_y \) along the \( x \)-direction. The normalized magnetic pattern of \( H_z \) has only an antinode at the center; thus, one may call this mode as resonant mode \((1,1)\). By observing the resonant mode patterns, one can know that the propagation phases inside the cavity along the \( x \)- and \( y \)-directions are both \( \pi/2 \). Thus, the wave vector of the propagating mode supported by the WHM constituting the cavity can be determined by \( k_x = \pi/2/L_x \) and \( k_y = \pi/2/L_y \). Then, by referring to Figure 2b, it is found that the propagating mode should have a working frequency of 0.717 GHz, nearly equal to that of resonant mode \((1,1)\), which illustrates that this resonant mode originates from the underlying WHM. When the cavity is put back into the air, resonant mode \((1,1)\) shifts to 0.890 GHz (Figure 3d).

**Figure 3.** WHM cavity. a) Schematic of a WHM cavity. The upper metal plate is removed for observation clarity. b) Cross section of the cavity. c-e) Electric and magnetic mode patterns on the intermediate cross section of the cavity. The left column is for \( E_x \), the middle column for \( E_y \), and the right column for \( H_z \). These are for resonant mode \((1,1)\) when the cavity is surrounded by a perfect magnetic conductor (PMC) condition or air, respectively, and e) this is for a surface-plasmon-like (SPL) mode when the cavity is in the air.

It should be pointed out that another kind of resonant modes can exist inside a WHM cavity besides the resonant modes depicted by the corresponding bulky propagation modes inside the WHM. For example, near resonant mode \((1,1)\) in Figure 3d, such a special resonant mode exists at 0.701 GHz (Figure 3e). For this mode, the components of \( E_x \) and \( H_y \) are mainly localized near the cavity boundaries, and the component of \( E_y \) does not change its sign along the \( y \)-direction. This resonant mode originates from the SPL waveguide mode along a metal–dielectric multilayer, which will be called a SPL resonant mode thereafter.

Due to the unique shapes of hyperbolic IFCs, the so-called anomalous scaling law predicts that narrowing a WHM cavity in one direction may decrease the resonance frequency counter-intuitively. To demonstrate this property, three other WHM cavities of different transverse sizes are investigated with the WHM cavity investigated in Figure 3d acting as a reference. Cavity 1 has a smaller thickness of \( L_y = 6 \text{ mm} \) compared with the reference cavity (the ceramic slab number is decreased). The propagating wave-vector component of \( k_y \) is required to increase to maintain the FP resonance condition, and this enforces resonant mode \((1,1)\) to blueshift according to Figure 2b. By simulation, it is found that the resonance frequency of cavity 1 does shift from 0.890 to 0.970 GHz, which is verified by Figure 4a. Cavity 2 has a smaller width of \( L_x = 6 \text{ mm} \) compared with the reference cavity (the ceramic slices are narrowed, and the number of the metal wires is also decreased correspondingly while each individual metal wire keeps unchanged). The propagating wave-vector component of \( k_x \) is also required to increase to maintain the FP resonance condition; thus, resonant mode \((1,1)\)
should be redshifted according to Figure 2b. As confirmed by simulation, the resonance frequency of cavity 2 is redshifted from 0.890 to 0.777 GHz (Figure 4b). The above-mentioned investigation shows that compressing the WHM cavity along the \(x\)- and \(y\)-directions produce opposite effects, which confirms the anomalous scaling behavior. The anomalous scaling law indicates that the working frequency of resonant mode (1,1) may change little when one simultaneously shrinks the width and thickness of the WHM cavity in some proportion. A cavity with \(L_x = L_y = 6\) mm is investigated in Figure 4c. The resonant frequency is 0.846 GHz, near that of the cavity in Figure 3d.

To achieve an ultrasmall cavity, the transverse size of the cavity in Figure 4c is further reduced to \(3 \times 3\) mm (one anorthite slice was sandwiched between two barium tetratitanate slices along the \(y\)-direction). For this extremely reduced structure, the pattern of resonant mode (1,1) still preserves (similar to the mode pattern of the \(10 \times 10\) mm cavity), as shown in Figure 4d, but the resonance frequency is shifted from 0.89 to 0.722 GHz. Compared with the free-space resonant wavelength \(\lambda_0 = 415.2\) mm, the present cavity is rather small, especially in the transverse size \(\lambda_0/138.4 \times \lambda_0/138.4 \times \lambda_0/6.9\). The quality factor has a moderate value \(Q_{\text{cav}} = 182\), and the mode dissipation mainly comes from the absorption loss of the metal wires.

In fact, a WHM cavity has a potential to possess a higher transverse confinement. As an example, two barium tetratitanate slices and one anorthite slice are alternately arranged (each slice is of \(200 \mu m \times 50 \mu m \times 54.2\) mm), and two metal wires \((20 \mu m \times 20 \mu m \times 54.2\) mm) are adopted on each large surface of the ceramic slices of high permittivity. This ultrasmall cavity is covered by two copper plates of 5 \(\mu\)m thickness at the top and bottom. Resonant mode (1,1) occurs at 0.823 GHz with \(Q_{\text{cav}} = 12.6\). This cavity \((1821 \times 2143 \times 6.7\) mm) is the smallest design in the transverse size as far as we know. It is further hoped to realize a 3D ultracompact cavity by reducing the height of the WHM cavity. Considering the FP resonance condition is fulfilled along the cavity height, this problem may be resolved using metamirrors supporting nonzero reflection phases or adopting higher permittivity dielectric materials.

### 2.4. Characterizing an Ultrasmall WHM Cavity

For experimental demonstration, the WHM cavity investigated in Figure 4c is correspondingly fabricated following the same geometry and material parameters, and the sample is shown in Figure 5a. In measurement, a coaxial cable connected with a vector network analyzer (Rohde & Schwarz ZVA40) acts as an electric-dipole antenna to stimulate and detect the cavity resonances, of which the cable core’s front part (about 120 mm in length) is made nude. Because the cavity modes are highly localized, their direct stimulation is difficult. Thus, the cavity

![Figure 4. Anomalous scaling law followed by WHM cavities. a,d) Normalized \(E_y\) distributions of resonant mode (1,1) for four cavities of different transverse sizes. Compared with the reference cavity in Figure 3, their transverse sizes are reduced to \(10 \times 6, 6 \times 10, 6 \times 6,\) and \(3 \times 3\) mm\(^2\), respectively, and the resonance frequencies are 0.970, 0.777, 0.846, and 0.722 GHz, respectively.](image)

![Figure 5. Characterizing a fabricated WHM cavity. a) Cavity sample. The insets represent the magnification of two different parts of the cavity. b) Measured \(S_{11}\) data. For comparison, the simulated result of \(S_{11}\) is also given by the dashed curve.](image)
is laid down upon a large copper substrate with a tiny gap of 0.1 mm (spaced by a layer of sticky tape) between them. The left cavity surface parallel to the y–z plane (see Figure 3a,b) faces the substrate. The copper substrate can force a larger part of mode pattern to reside in the surrounding environment.

The corresponding measured result of $S_{11}$ is shown in Figure 5b. A resonant mode with $Q_{cav} = 95$ is observed at 0.709 GHz. This mode corresponds to resonant mode (1,1) shown in Figure 3d. In simulation, the introduction of the copper substrate shifts the resonance frequency from 0.722 to 0.73 GHz with $Q_{cav}$ nearly unchanged (the dashed curve in Figure 5b represents the numerical result of $S_{11}$ obtained by the full-wave software of CST Microwave Studio). The deviation between the measured and numerical results is induced by the fabrication error. In Figure 5b, one can also observe another resonant mode at 0.652 GHz with $Q_{cav} = 55$. This corresponds to the SPL resonant mode shown in Figure 3e, whose simulated resonance frequency is 0.665 GHz with $Q_{cav} = 111$.

3. Conclusion

In conclusion, the waveguide approach allows for the construction of new-type microwave HMs. Ultrahigh wave vectors have been confirmed by the construction of ultrasmall WHM cavities. The anomalous scaling law has also been examined for WHM cavities. Our suggestion enables flexible variation of HMs, eliminating the limit of wire-type HMs in the microwave regime. As a low-loss platform, WHMs are predicted to flexibly enable distinctive phenomena in the microwave regime, and find their potential roles in many aspects, including microwave imaging and sensing, microwave communicating and integrating, controlling the behavior of microwave transition, and Cerenkov electron radiation. The proposed WHMs are potentially scalable across the electromagnetic spectrum from radio to terahertz to extend their significance.

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Conflict of Interest

The authors declare no conflict of interest.

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[1] A. Podrubny, I. Iorsh, P. Belov, Y. Kivshar, Nat. Photonics 2013, 7, 948.
[2] L. Ferrari, C. Wu, D. Lepage, X. Zhang, Z. Liu, Prog. Quantum Electron. 2015, 40, 1.
[3] D. R. Smith, D. Schurig, J. J. Mock, P. Kolinko, P. Rye, Appl. Phys. Lett. 2004, 84, 2244.
[4] Z. Liu, H. Lee, Y. Xiong, C. Sun, X. Zhang, Science 2007, 315, 1686.
[5] P. A. Belov, C. R. Simovski, P. Ikonen, Phys. Rev. B 2005, 71, 193105.
[6] H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, V. M. Menon, Science 2012, 336, 205.
[7] D. Lu, J. J. Kan, E. E. Fullerton, Z. Liu, Nat. Nanotechnol. 2014, 9, 48.
[8] J. Shi, B. Liu, P. Li, L. Y. Ng, S. Shen, Nano Lett. 2015, 15, 1217.
[9] Y. Guo, C. L. Cortes, S. Molesky, Z. Jacob, Appl. Phys. Lett. 2012, 101, 131106.
[10] X. Yang, J. Yao, J. Rho, X. Yin, X. Zhang, Nat. Photonics 2012, 6, 450.
[11] F. Ding, Y. Cui, X. Ge, Y. Jin, S. He, Appl. Phys. Lett. 2012, 100, 103506.
[12] E. Yozhall, M. Schnell, A. Y. Nikitin, O. T voxelera, A. Woessner, M. B. Lundeberg, F. Casanova, L. E. Hueso, F. H. L. Koppens, R. Hillenbrand, Nat. Photonics 2015, 9, 674.
[13] Y. He, S. He, J. Gao, X. Yang, J. Opt. Soc. Am. B Opt. Phys. 2012, 29, 2559.
[14] N. Maccaferr, Y. Zhao, T. Isoniemi, M. Iarossi, A. Parraccino, G. Strangi, F. De Angelis, Nano Lett. 2019, 19, 1851.
[15] P. Wang, A. V. Krasavin, F. N. Viscomi, A. M. Adawi, J.-S. G. Bouillard, L. Zhang, D. J. Roth, L. Tong, A. V. Zayats, Laser Photonics Rev. 2018, 12, 1800179.
[16] W. Gao, M. Lawrence, B. Yang, F. Liu, F. Fang, B. Béri, J. Li, S. Zhang, Phys. Rev. Lett. 2015, 114, 037402.
[17] A. V. Kabashin, P. Evans, S. Pastkovsky, W. Hendren, G. A. Wurtz, R. Atkinson, R. Pollard, V. A. Podolskiy, A. V. Zayats, Nat. Mater. 2009, 8, 867.
[18] K. V. Sreekanth, Y. Alapan, M. Elkabbash, E. Ilker, M. Hinczewski, U. A. Gurkan, A. De Luca, G. Strangi, Nat. Mater. 2016, 15, 621.
[19] L. H. Nicholls, F. J. Rodríguez-Fortuño, M. E. Nasir, R. M. Córdova-Castro, N. Olivier, G. A. Wurtz, A. V. Zayats, Nat. Photonics 2017, 11, 628.
[20] G. A. Wurtz, R. Pollard, W. Hendren, G. P. Wiederrecht, D. J. Gosztoła, V. A. Podolskiy, A. V. Zayats, Nat. Nanotechnol. 2011, 6, 107.
[21] S. Dai, Z. Fei, Q. Ma, A. S. Rodin, M. Wagner, A. S. McLeod, M. K. Liu, W. Gannett, W. Regan, K. Watanabe, T. Taniguchi, M. Thiemens, G. Dominguez, A. H. C. Neto, A. Zettl, F. Keilmann, P. Jarillo-Herrero, M. M. Fogler, D. N. Basov, Science 2014, 343, 1125.
[22] J. D. Caldwell, A. V. Kretinin, Y. Chen, V. Giannini, M. M. Fogler, Y. Francescato, C. T. Ellis, J. G. Tischler, C. R. Woods, A. J. Giles, M. Hong, K. Watanabe, T. Taniguchi, S. A. Maier, K. S. Novoselov, Nat. Commun. 2014, 5, 5221.
[23] W. Ma, P. Alonso-González, S. Li, A. Y. Nikitin, J. Yuan, J. Martín-Sánchez, J. Taboada-Gutierrez, I. Amenabar, P. Li, S. Vélez, C. Tollan, Z. Dai, Y. Zhang, S. Sriram, K. Kalantar-Zadeh, S.-T. Lee, R. Hillenbrand, Q. Bao, Nature 2018, 562, 557.
[24] C. R. Simovski, P. A. Belov, A. V. Atrashchenko, Y. S. Kivshar, Adv Mater 2012, 24, 4229.
[25] Y. Yang, L. Jing, L. Shen, Z. Wang, B. Zheng, H. Wang, E. Li, N.-H. Shen, T. Koschny, C. M. Soukoulis, H. Chen, NPG Asia Mater. 2017, 9, e428.
[26] A. A. Orlov, P. M. Voroshilov, P. A. Belov, Y. S. Kivshar, Phys. Rev. B 2011, 84, 045424.
[27] R. Macêdo, K. L. Livesey, R. E. Carney, Appl. Phys. Lett. 2018, 113, 121104.
[28] C. Lan, K. Bi, J. Zhou, B. Li, Appl. Phys. Lett. 2015, 107, 211112.
[29] C. Della Giovampaola, N. Engheta, Phys. Rev. B 2016, 93, 195152.
[30] Z. Li, L. Liu, H. Sun, Y. Sun, C. Gu, X. Chen, Y. Liu, Y. Luo, Phys. Rev. Appl. 2017, 7, 044028.
[31] H. Cao, J. Wiersig, Rev. Mod. Phys. 2015, 87, 61.
[32] J. T. Shen, P. B. Catrysse, S. Fan, Phys. Rev. Lett. 2005, 94, 197401.
[33] M. Choi, S. H. Lee, Y. Kim, S. B. Kang, J. Shin, M. H. Kwak, K.-Y. Kang, Y.-H. Lee, N. Park, B. Min, Nature 2011, 470, 369.
[34] W. Hu, Y. Liu, R. L. Withers, T. J. Frankcombe, L. Norén, A. Snashall, M. Kitchin, P. Smith, B. Gong, H. Chen, J. Schiemer, F. Brink, J. Wong-Leung, Nat. Mater. 2013, 12, 821.
[35] I. M. Reaney, D. Iddles, J. Am. Ceram. Soc. 2006, 89, 2063.
[36] I. Avrutsky, I. Salakhutdinov, J. Elser, V. Podolskiy, Phys. Rev. B 2007, 75, 241402.