ADVANCED PHYSICS RESEARCH
Open Access
www.advphysicsres.com

Engineering Epsilon-Near-Zero Media with Waveguides

*Peihang Li, Wendi Yan, Shuyu Wang, Pengyu Fu, Yongjian Zhang, and Yue Li**

Epsilon-Near-Zero (ENZ) media have attracted widespread interest due to their unique electromagnetic properties, which have brought distinctive characteristics and phenomena, such as spatiotemporal decoupling, supercoupling and tunneling, constant phase transmission, near-field enhancement, and so on. However, these ENZ characteristics are existed in natural plasmonic materials at their intrinsic plasma frequencies and accompanied by significant losses, thus limiting their applications in engineering. Different from the effect ENZ media with artificially periodic structures, the waveguide ENZ media offers a promising platform with non-periodic architectures. Unlike the natural plasmonic materials and the periodic-structured ENZ media, the waveguide ENZ media utilizes waveguide dispersion to achieve effective ENZ characteristics and phenomena with lower loss and smaller dimensions. This review begins with an exploration of the fundamental properties of the waveguide ENZ media and then introduces the design principles of different ENZ-based electromagnetic devices. Finally, the review concludes with the challenges and potential development directions encountered by the ENZ media in the realm of electromagnetic applications.

1. Introduction

Since the introduction of Maxwell's equations, we have been afforded a profound insight into the propagation laws of electromagnetic waves in the physical world through the theoretical framework they establish.[1] The propagation behavior of electromagnetic waves in space is elegantly and succinctly represented, while the diversity of phenomena in the physical world is described by constitutive equations. By artificially designing and constructing unique distribution of ϵ and μ, we can achieve remarkable manipulations of electromagnetic waves. Specifically, through carefully designed structures, optical parameters can exhibit zero values instead of the typical positive value.[2] Among the myriad optical media, the epsilon-near-zero (ENZ) structure is particularly distinctive. In optical media, the wavenumber of electromagnetic waves is directly linked to the dielectric constant of the media. When the magnetic permeability $\mu = 1$ and the dielectric constant $\epsilon \approx 0$, the wavenumber $k \approx 0$.[3,4] This results in unique phase uniformity distribution and remarkable physical size insensitivity – the optical path travelled by electromagnetic waves in ENZ media is zero. This phenomenon allows for decoupling the operating frequency from the device size and location, enabling the realization of optical manipulation devices such as invisibility cloaking,[5,6] size-independent resonators,[7–9] radiator structures,[10–12] supercoupling and tunneling waveguides,[3,13–19] and position-insensitive doping structures.[20] On the other hand, in ENZ media, the electromagnetic wave induces an electric displacement field of 0, leading to a significant discontinuity. This discontinuity enables spontaneous enhancement or suppression of the electric field in the media's vicinity, offering opportunities for modulating nonlinear effects[21–23] and Purcell factors.[24–27] This unique property of ENZ media has already demonstrated remarkable capability in modulating the amplitude and phase of electromagnetic waves. It has been utilized in microwave devices, integrated optics, and optoelectronic devices, demonstrating great application potential.

Several methods can be employed to realize ENZ media, including natural plasma materials, periodic structures ENZ media, and waveguide ENZ media. In the optical band, ENZ media can be directly obtained from natural plasma materials near the corresponding plasma frequency.[28–30] Numerous studies have explored the application of natural plasma materials in various fields such as lasers,[31–33] photocatalysis,[34,35] optical quantum,[36–38] and nonlinear enhancement.[39,40] Figure 2g illustrates the optical parameter profile of Ag near its plasma frequency. When the real part of the dielectric constant (ϵ) approaches zero, the material exhibits a significant imaginary part, indicating that natural plasma materials typically incur large losses. Moreover, natural plasma materials often feature fixed ENZ bands, limiting ability to define and design the frequency bands of ENZ to meet practical engineering and research requirements. Periodic structures ENZ media enable modulation of overall optical parameters through carefully designed periodic structures.[41–43] This provides greater flexibility, allowing for the modulation of the operating frequency through pattern

---

P. Li, W. Yan, S. Wang, P. Fu, Y. Zhang, Y. Li
Department of Electronic Engineering
Tsinghua University
Beijing 100084, China
E-mail: lyee@tsinghua.edu.cn

Y. Li
Beijing National Research Center for Information Science and Technology
Beijing 100084, China

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/apxr.202400070

DOI: 10.1002/apxr.202400070

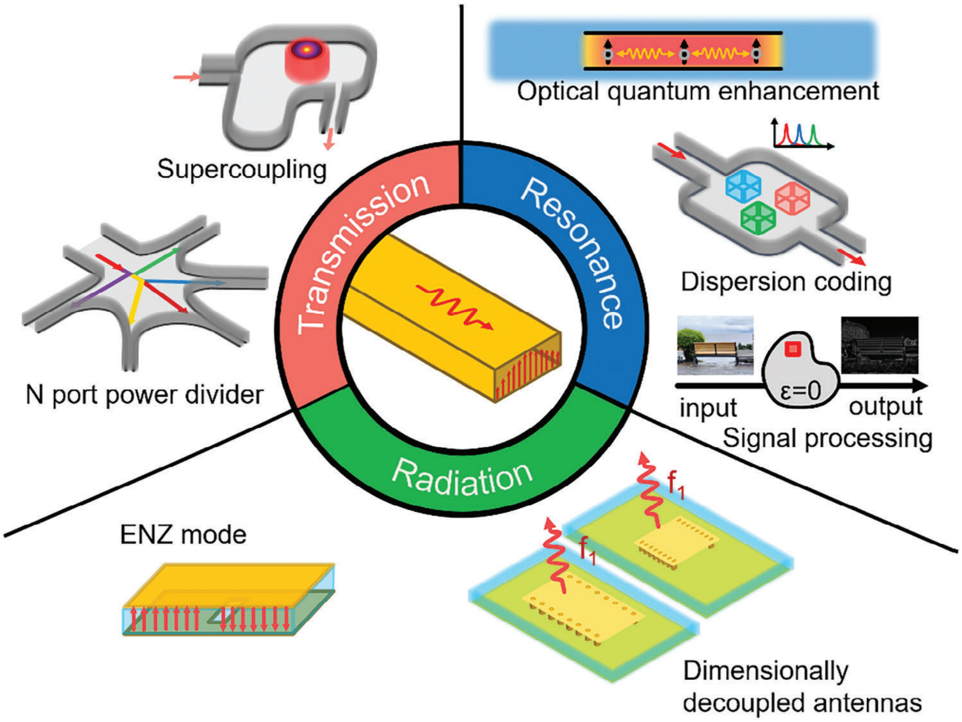

Figure 1. Three directions of application of waveguide ENZ media: transmission, resonance, and radiation.

design.[44,45] A generalized dielectric constant spectrogram for periodic structures ENZ media is depicted in Figure 2h. The ENZ properties of periodic structures ENZ media typically emerge at the resonance frequency center of the spectrum, accompanied by sharp spectral phase changes. However, the dimensions of periodic structures ENZ media units often approach the scale of the wavelength, requiring the etching of complex patterns. This results in elevated manufacturing costs for the devices. Therefore, both above methods are constrained in practical engineering applications.

To complement and explore the above two types of ENZ media, another method for constructing ENZ media has been proposed.[3] By leveraging the structural dispersion of waveguides, we can achieve equivalent ENZ structures near the cutoff frequency of the waveguide, as illustrated in Figure 2f. As the frequency of an electromagnetic wave approaches the cutoff frequency of a waveguide, the longitudinal propagation constant tends toward infinity, resulting in nearly in-phase propagation within the waveguide. It has been demonstrated in various waveguides and cavities that the equivalent dielectric constant near their cutoff frequency can be considered as 0.[3,46,47] Waveguide ENZ media has simple structure and due to its inherent waveguide properties, we can easily integrate into transmission devices. On the other hand, because there are no additional resonant structures, waveguide ENZ media can also avoid the significant losses associated with traditional plasmonic materials, especially in air-guided waveguides. The combination of low loss and structural simplicity described above has prompted increased attention and development in the field of waveguide ENZ media. A variety of devices based on waveguide ENZ media have been developed, including supercoupling and tunneling waveguides,[13,17,48,49] impedance matching networks,[50] wavefront shaping devices,[51,52] directional radiators,[30,53,54] localized near-field enhancement devices,[30,55–57] and microwave computational networks,[58,59] as shown in **Figure 1**.

In this review, we introduce various unique electromagnetic manipulation features of ENZ media at a theoretical level based on the electromagnetic wave propagation principle, starting from the unique electromagnetic properties of waveguide ENZ media. Furthermore, we will introduce the dispersion modes and operating principles of waveguide ENZ media. Subsequently, we will delve into the specific engineering applications of waveguide ENZ media in both microwave and photonics domains. We will present a comprehensive overview of innovative research results on waveguide ENZ dielectrics, focusing on three key physical properties: transmission, resonance, and radiation. Finally, we will provide a summary and outlook on the future development of waveguide ENZ media.

2. Basic Concepts of Waveguide ENZ Media

Waveguide ENZ media exhibit numerous unique optical properties. In the following sections, we will provide fundamental theoretical derivations by incorporating the dispersion properties of waveguide ENZ media. Additionally, we will explore various counterintuitive physical characteristics of ENZ media.

2.1. From Waveguide Dispersion to Waveguide ENZ Media

As discussed earlier, there are multiple methods to design ENZ media. Several natural plasma materials exhibit ENZ properties in the optical or infrared bands. However, the fixed ENZ

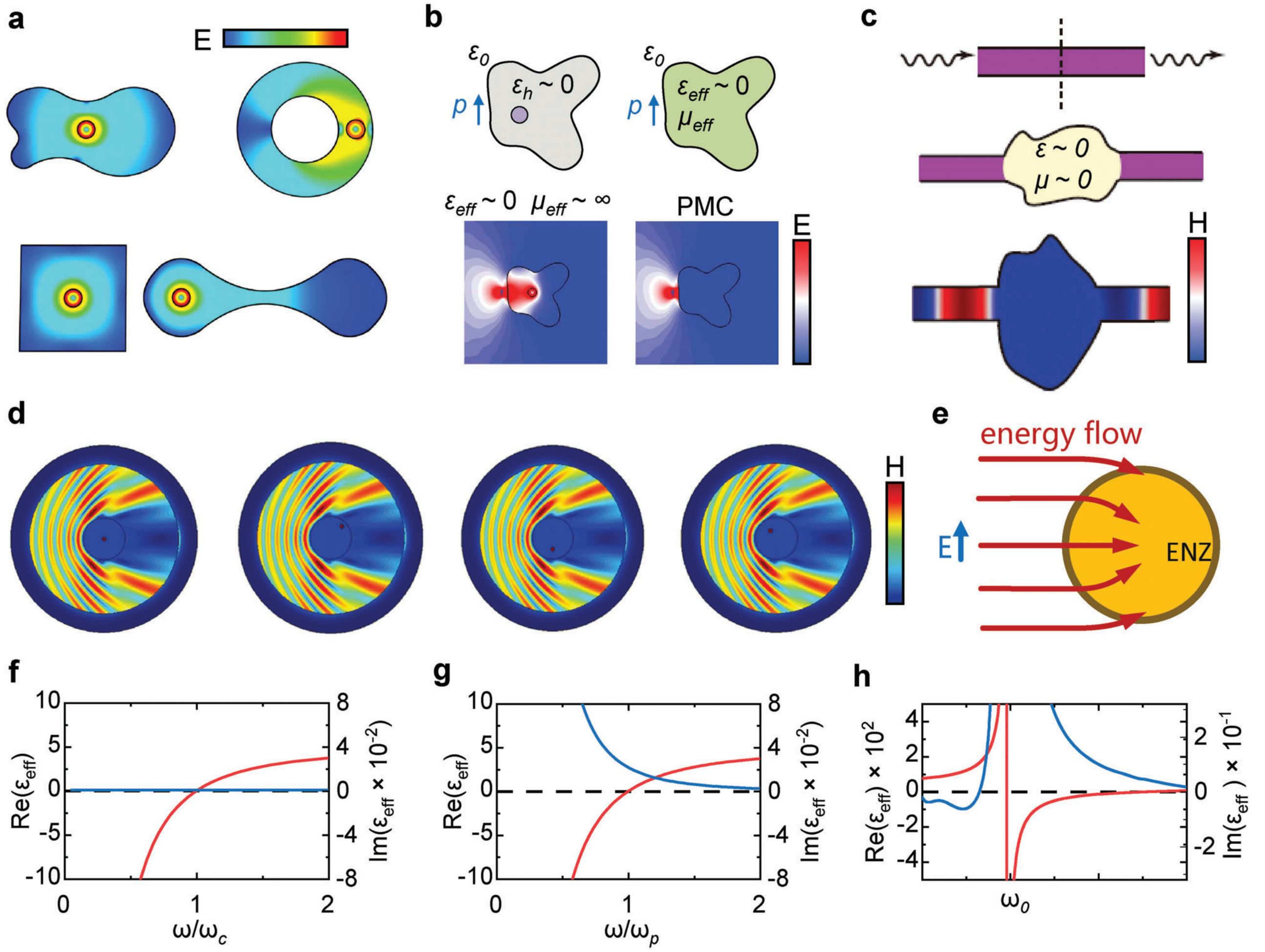

Figure 2. Properties of the ENZ media. a) Size-independent resonant cavities based on ENZ.[7] Licensed under the Creative Commons Attribution 4.0 International. b) Photonic doping of ENZ media.[14] Licensed under the Creative Commons Attribution 4.0 International. c) The phenomenon of supercoupling and tunneling in ENZ media.[62] Reproduced with permission. Copyright 2014, Nat Commun. d) Positional irrelevance of photonic doping;[63] Reproduced with permission. Copyright 2017, IEEE. e) Near-field electric field focusing on ENZ media. f) Effective permittivity of the waveguide ENZ media. g) Effective permittivity of Ag near the plasma frequency. h) Effective permittivity of typical periodic structures ENZ media near the resonant frequency.

band, and high losses of natural plasma materials, along with the large electrical sizes and complex fabrication processes of periodic structures ENZ media, limit their engineering applications. Waveguide ENZ media can overcome the engineering application challenges of both types of ENZ media. **Figure 2f** illustrates the dielectric constant spectrum of waveguide ENZ media. When the frequency of electromagnetic waves is near the waveguide cutoff frequency, the dielectric constant of waveguide ENZ media tends toward zero, while maintaining a lower imaginary part. This characteristic enables waveguide ENZ media to exhibit lower losses. Additionally, we can adjust the working frequency of ENZ by changing the waveguide width, providing significant flexibility in engineering manufacturing. This non-periodic architecture allows for the easy realization of subwavelength-scale ENZ device designs. In summary, the lower losses, greater design freedom, and non-periodic small size architecture of waveguide ENZ media confer advantages in engineering applications.

In the waveguide ENZ media, ENZ modes are realized using waveguide dispersion. As early as the 1960s, Rotman demonstrated that parallel-plate or rectangular waveguides can simulate plasmonic media when operating below the cutoff frequency of the TE_{10} mode.[46,60] Taking the fundamental mode of a rectangular waveguide as an example, the propagation constant β of the waveguide can be expressed as:

$$\beta = k_0 \sqrt{\varepsilon_r - \left(\frac{\lambda}{2a}\right)^2} \tag{1}$$

where λ represents the wavelength of the electromagnetic wave, k_0 is the wave number in free space, a denotes the width of the rectangular waveguide. Moreover, through the propagation constant of the waveguide, we can derive the effective dielectric constant of the waveguide:

$$\varepsilon_{eff} = \left(\frac{\beta}{k_0}\right)^2 = \varepsilon_r - \left(\frac{\lambda}{2a}\right)^2 \tag{2}$$

As depicted in Figure 2f, when the electromagnetic wave frequency approaches the cutoff frequency, the effective dielectric constant of the waveguide tends toward zero, transitioning to negative and positive values below and above the cutoff frequency, respectively. It is noteworthy that waveguide losses are minimal, providing significant design flexibility for the integration of small-scale devices due to their non-periodic structure. Various waveguide structures can be used to realize waveguide ENZ media, such as metallic rectangular waveguides, flat waveguides, and SIW waveguides.

2.2. Physical Properties of Waveguide ENZ Media

2.2.1. The Spatiotemporal Decoupling of Waveguide ENZ Media

Among the various properties of waveguide ENZ media, one of the most fascinating is its spatiotemporal decoupling characteristic. From a physical perspective, the wavevector of ENZ media is considered infinitely small, and the effective wavelength is considered infinitely long. In terms of optical path length, the propagation of electromagnetic waves in waveguide ENZ media is "ineffective," with phase being uniform. In the wave equation, the spatial variation factors of the electromagnetic field are represented by $\nabla^2 \boldsymbol{E}$ and $\nabla^2 \boldsymbol{H}$, while the temporal variation factors are reflected in $\partial^2 \boldsymbol{E}/\partial t^2$ and $\partial^2 \boldsymbol{H}/\partial t^2$. This implies that the spatial and temporal characteristics of the electromagnetic field distribution are mutually coupled, and temporal properties are directly influenced by boundary conditions and material parameters. We can only set the operating frequency of devices by precisely adjusting the boundary conditions. However, in ENZ media where $\epsilon \approx 0$, the spatial and temporal factors are decoupled.[13,61,62]

Ref. [7] discusses in detail the possibility of utilizing ENZ media to achieve geometrically decoupled resonant cavities, as shown in Figure 2a. The eigenfrequency of the resonant cavity depends entirely on the nature of the internal particles and the cross-sectional area of the ENZ media, which allows us to arbitrarily change the geometry without altering the intrinsic frequency of the resonant cavity, enabling decoupling of dimensions. On the other hand, the positions of the particles inside the ENZ media are also decoupled, and the overall modulation characteristics of the ENZ media for electromagnetic waves are shown to be independent of the positions of the particles inside,[63] as shown in Figure 2d.

In addition to the resonance of electromagnetic waves, furthermore, the spatiotemporal decoupling characteristic of waveguide ENZ media can be applied to the transmission of electromagnetic waves. Consider a transmission waveguide: if the dimensions of the waveguide are decoupled from the transmission frequency, we can freely change the size and shape of the waveguide without introducing additional reflection and discontinuity, thus affecting the transmission efficiency of the waves. ref. [62] proves that waveguide ENZ media can achieve the supercoupling and tunneling effect. As shown in Figure 2c, electromagnetic waves exhibit remarkable uniform phase distribution and achieve decoupling transmission through waveguides of arbitrary shapes. However, achieving the supercoupling and tunneling effect requires not only the dielectric constant of the media to be 0 but also an appropriate magnetic permeability.[14] We can understand this phenomenon from the perspective of wave impedance. When $\mu = 1$ and $\epsilon \approx 0$, the wave impedance of the media η approaches infinity, implying a reflection coefficient of 100% at the ports. Therefore, to achieve impedance matching, we also need to adjust the magnetic permeability of the media to realize the supercoupling and tunneling effect.

2.2.2. Doping of ENZ Media

The concept of doping originates from semiconductor physics, where impurities are intentionally introduced into a single medium to control its macroscopic properties.[64] With the emergence of artificial metamaterials, this concept has been extended to optics and electromagnetics.[65,66] However, the traditional doping equivalence in electromagnetic waves requires three conditions to be met: the object must contain enough dopants, the dopant size and separation distance must be much smaller than the wavelength.[67] As the number of dopants decreases and their sizes increase, this equivalence process inevitably fails. This limitation restricts the application of this paradigm in macroscopic photonic systems. In waveguide ENZ media the constraints related to doping are overcome. As discussed earlier, the spatiotemporal decoupling ability of ENZ media allows electromagnetic waves to exhibit nearly infinite phase velocity and quasi-static field distribution. Consequently, dopants in waveguide ENZ media are perceived as electrically small, regardless of their size. We can alter the properties of the entire system by placing dopants of any shape at arbitrary positions within the waveguide ENZ media,[14] as shown in Figure 2b. ref. [14] provides a detailed discussion on the theoretical process of doping in ENZ media. Considering an ENZ media main body of arbitrary shape with a cross-sectional area A, containing multiple dopants with a cross-sectional area A_d, and relative permittivity and permeability set as ϵ_d and μ_d respectively, the effective optical parameters μ_eff of the doped ENZ media can be obtained through the electromagnetic field boundary value problem:

$$\mu_\mathrm{eff} = 1 + \sum_{d} \Delta\mu_d, \quad \varepsilon_{eff} = 0 \tag{3}$$

$$\Delta\mu_\mathrm{d} = \frac{1}{A}\left[\int_{A_d} \Psi^d(\boldsymbol{r})\, dA - A_d\right] \tag{4}$$

here, $\Psi^d(\boldsymbol{r})$ represents the normalized magnetic field distribution within the dopants, with the magnetic field at the boundary set to 1 (the magnetic field is uniform in ENZ media). Using the above equation, we can adjust the overall system permeability by adding arbitrary dopants at any positions within the waveguide ENZ media while maintaining the near-zero dielectric constant characteristic, providing an opportunity to set the wave impedance of waveguide ENZ media. For instance, as discussed in the previous section, waveguide ENZ media exhibit supercoupling and tunneling characteristics. However, due to their wave impedance approaching infinity, the reflection coefficient of electromagnetic waves incident from conventional media into waveguide ENZ media is 100%. By doping ENZ media, we can achieve wave impedance matching between the waveguide ENZ media and conventional media, thereby constructing supercoupling and tunneling structures.

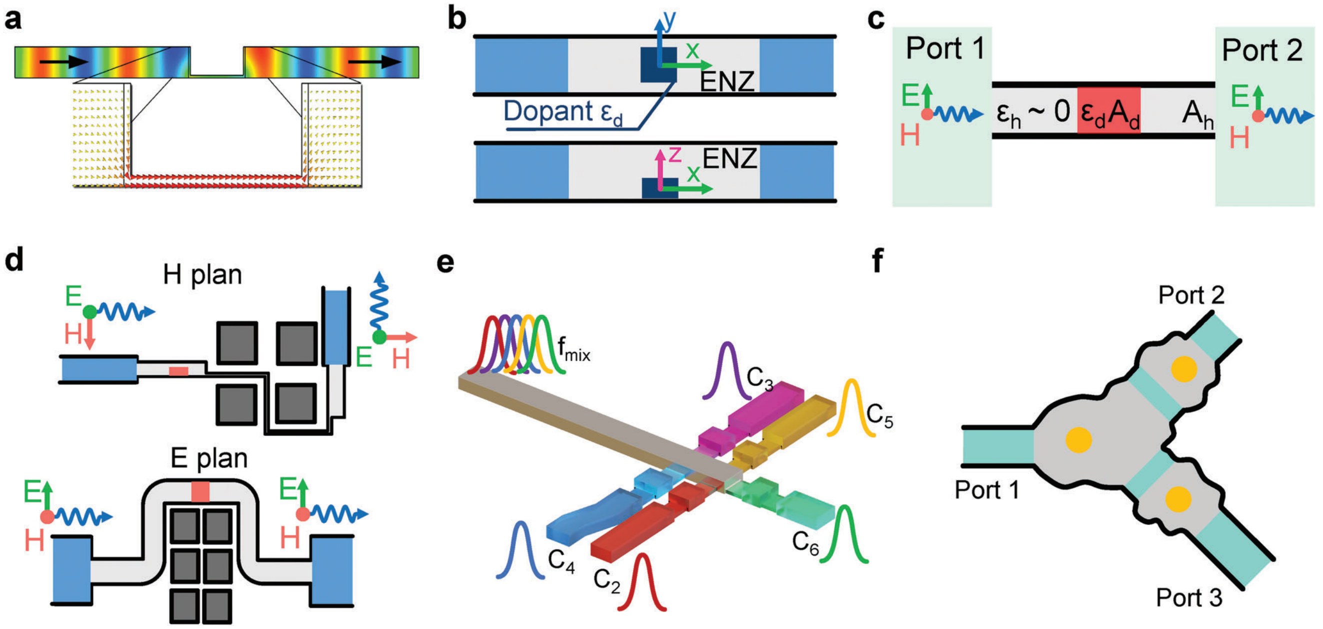

Figure 3. a) Adjusting the cross-sectional area of the ENZ to achieve impedance matching.[3] Reproduced with permission. Copyright 2008, Phys. Rev. Lett. b) Resonance-type doping in waveguide ENZ media supercoupling and tunneling.[15] c) Transmission-type doping in waveguide ENZ media supercoupling and tunneling.[17] d) Waveguide ENZ media propagation in complex electromagnetic environments e) Five-channel frequency-division mutipliexing and demultiplexing based on waveguide ENZ media supercoupling and tunneling.[77] f) Transmission-reflection decoupling of waveguide ENZ media.[19]

2.2.3. Near-Field Enhancement and Suppression of Waveguide ENZ Media

Utilizing plasmonic media and photonic crystals to achieve light field enhancement beyond the diffraction limit has been a significant research direction in quantum computing, photodetection, and photocatalysis.[68,69] This is primarily attributed to the remarkably high local density of optical states (LDOS) inherent in such media, which significantly amplifies the nonlinear effects of media and intensifies the spontaneous emission of photon emitters. aveguide ENZ media also possess the capability of near-field enhancement and suppression. When electromagnetic waves interact with ENZ media, the boundary conditions dictated by Maxwell's equations lead to a significant discontinuity in the electric field at the material interface, as illustrated in Figure 2e, resulting from the electric displacement vector being zero within the ENZ media. Near the ENZ media, this discontinuity spontaneously enhances or suppresses the electric field, thereby offering avenues for enhancing nonlinear effects and Purcell enhancement. It has also been demonstrated that waveguides with equivalent ENZ media properties can be similarly employed to enhance or suppress nonlinear effects and spontaneous emission from single photon sources.[70,71]

In this chapter, we have explored the remarkable physical properties of ENZ media and the physical characteristics of waveguide ENZ media. Next, we will delve into research findings and advancements within the field through three typical application scenarios of waveguide ENZ media: transmission, resonance, and radiation.

3. The Transmission of Waveguide ENZ Media

Based on the unique electromagnetic characteristics supported by waveguide ENZ media, a variety of applications have been investigated. According to their application scenarios, these applications can be mainly categorized into three types, including the transmission applications, resonance applications, and radiation applications. In this section, we focus on the transmission applications.

3.1. Waveguide Transmission Line

The characteristics of ENZ media mentioned above have demonstrated the potential for various control of electromagnetic waves propagation in ENZ media. Compared with classical methodology for transmitting electromagnetic waves in metal waveguide, the most specific property of the waveguide ENZ media is the supercoupling and tunneling. The supercoupling and tunneling demonstrates the capability of electromagnetic waves to be "squeezed" and tunneled through channels much narrower than their wavelengths, and provides the potential of overcoming the sharp bends, corners, and obstacles in the waveguide. As for a general waveguide ENZ media supercoupling and tunneling model in **Figure 3**a, which consists of an arbitrary-shaped waveguide ENZ media channel with the area A_p connecting two rectangular ports with the widths a_1 and a_2, the reflection coefficient of the excited Port 1 can be described as:[13]

$$\rho = \frac{(a_1 - a_2) + ik_0\mu_{r,p}A_p}{(a_1 + a_2) - ik_0\mu_{r,p}A_p} \tag{5}$$

where k_0 is the propagation constant of electromagnetic waves in vacuum and $\mu_{\mathrm{r,p}}$ is the relative permeability of media in both the ENZ channel and ports. "i" is the imaginary unit and an $e^{-i\omega t}$ time convention is first assumed and suppressed. To enable EM waves to tunnel perfectly through the narrow channel, it is necessary that $a_1 \approx a_2$ and that $k_0\mu_{\mathrm{r,p}}A_{\mathrm{p}}$ is as small as possible. To realize this goal, two methods can be employed. First, we can reach a near-zero A_{p} through a tunneling channel with a width approaching zero. Second, we can adjust $\mu_{\mathrm{r,p}}$ near zero through the photonic doping methodology mentioned above. Several experiments have been realized to verify the concept of supercoupling and tunneling through these two methods.

The first experimental implementation of ENZ supercoupling and tunneling is reported in ref. [3] and [72]. The schematics of both experiments are depicted in Figure 3a. Ultranarrow waveguide channels, which are filled with waveguide ENZ media, are used to connect the rectangular input and output ports, respectively. Via the reasonable adjusting of the height and length of channels, the measurements demonstrate a zero-phase electromagnetic waves transmission, which is the sign of the establishment of the supercoupling and tunneling. However, since channels cannot be infinitely narrow, the transmission losses are introduced during the electromagnetic wave propagation. ref. [72] report a −5 dB transmission efficiency, while ref. [3] report a −6 dB transmission efficiency. Besides, these experimental setups propose a huge discontinuity in the E-plane, which is difficult for the planar integration applications. It is necessary to adopt a new method to enhance its transmission efficiency.

Take inspiration in the methodology of photonic doping, the $\mu_{\mathrm{r,p}}$ can be adjusted through implant a dielectric rod in the waveguide ENZ media. Therefore, we can reach a $\mu_{\mathrm{r,p}}$ near zero to maximize the transmission coefficient in an ENZ channel with finite height. Two types of photonic doping have been researched, including a resonance-type doping[15] and a transmission-type doping.[17] First, ref. [15] report a supercoupling waveguide with the uniform profile assisted by resonance-type doping. For easily integration, a rectangular dopant with the height h_{d} and length l_{d}, together with the image principle, is used to replace the circular dopant reported in ref. [14]. Around the resonant frequency of the dopant, the effective relative permeability $\mu_{\mathrm{r,p}}$ of the entire ENZ media will be adjusted near zero. Hence, ENZ supercoupling and tunneling occurs in a waveguide with the uniform profile, which is fabricated by the substrate-integrated-waveguide (SIW) technique. At the ideal case, the transmission amplitude can reach 100% for lossless dopant. However, the experiment only proposes a transmission efficiency at ≈60% (−4.5 dB), due to the strong resonance in the lossy dielectric dopant.

In order to further enhance the transmission efficiency, the transmission-type doping[17] are used to assist to the supercoupling and tunneling.[73] As depicted in Figure 3c, different from the resonance-type doping, a dielectric rod, with both top and bottom edges in contact with the perfect electric conductor (PEC) boundaries, is located in the center of the waveguide channel. The proposed transmission-type doping replaces high-quality-factor 2D resonant modes with low-quality-factor 1D modes, such that losses caused by resonant dopants are reduced. A 80% transmission efficiency and zero-phase advance in ENZ supercoupling and tunneling is achieved and observed in experiments. This is the highest efficiency that can be observed in the supercoupling and tunneling experiment. In summary, we introduce three approaches to achieve the ENZ supercoupling and tunneling in the waveguides, including an ultranarrow channel, assistance by the resonance-type doping and assistance by the transmission-type doping.

Based on waveguide ENZ media supercoupling and tunneling, several devices, with exotic functions, have been researched. Thanks to the potential of supercoupling in overcoming the sharp bends, corners, and obstacles in the waveguide, researchers can design waveguides to adapt to the propagation of electromagnetic waves in complex scenarios. These waveguides have arbitrary shapes, just like optical fibers used for light propagation, and are thereby referred to as "electric fibers". As demonstrated in Figure 3d, refs. [15] and [17] demonstrate two types of electric fibers for overcoming the discontinuity in E-plane and H-plane, respectively. The insert losses of "electric fibers" are less than 1 dB. The electric fibers, based on high-efficiency waveguide ENZ media supercoupling and tunneling, provide a potential alternative for low-loss conduits in waveguide-integrated structures, which is of great significance for the development of microwave-integrated devices. Some researchers suggest that this intriguing waveguide ENZ media supercoupling phenomenon operates under similar physical principles as ideal fluids, and it can be likened to an optical system with turbulence suppression capabilities. This conceptualization offers a novel perspective for comprehending waveguide ENZ media.[74,75] On the other hand, research has also focused on increasing the bandwidth of supercoupling waveguides. The ref. [76] discusses a method for realizing wideband ENZ supercoupling, and a waveguide crossover is further proposed and experimentally verified that it can realize wideband dual-narrow-channel full transmission in one medium layer with a very low profile.

Expect from the high efficiency electromagnetic wave progradation, supercoupling and tunneling also provides the possibilities for multi-frequencies. ref. [77] has reported a frequency-division multiplexing application. As depicted in Figure 3e, a five-channel frequency-division multiplexing and demultiplexing in the millimeter-wave range is realized. Here, C_1 is the input port conveying a broadband signal multiplexing 5 frequencies, and C_2 to C_6 are the output ports for demultiplexing signals. It is attributed to the frequency-selective tunnelling effect of the low-loss waveguide ENZ media. Specifically, supercoupling only occurs near the cutoff frequency of the TE_{10} mode of the waveguide ENZ media and allows the electromagnetic waves to tunnel through the narrow waveguide ENZ media despite the large impedance mismatch at its entrance and exit faces. Hence, transmitted frequencies f_{a} to f_{e} are determined by the sizes and Q factors of waveguides C_2 to C_6, which can be tuned reasonably. This strategy of frequency-division multiplexing, based on waveguide ENZ media supercoupling and tunneling, may pave a way for efficiently allocating the spectrum for future communication networks.

Besides general supercoupling for reflectionless total transmission with zero-phase advance, Waveguide ENZ media also allow for independent control over the amplitude and the phase of the transmission and reflectionless waves.[19] Figure 3f demonstrates a device, including three different hosts doping with dielectric rods with different permeability. By manipulating the permittivity of dopants with extremely low loss or gain, various

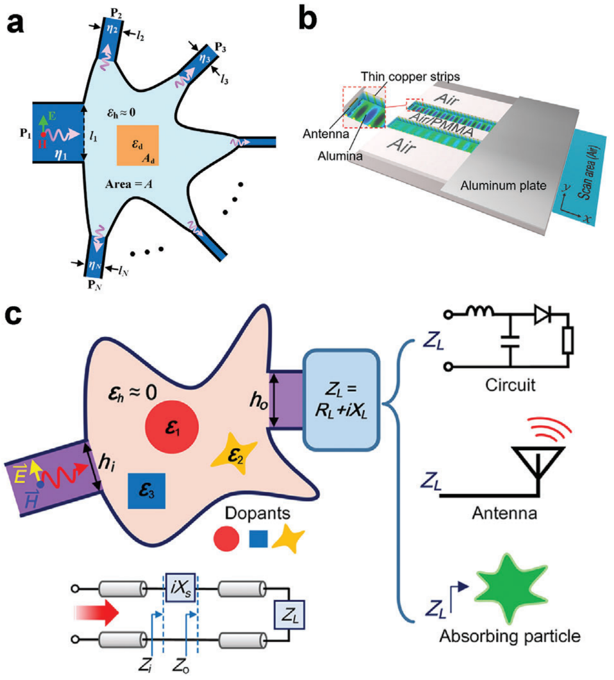

Figure 4. a) N-way power divider based on waveguide ENZ media.[50] Reproduced with permission. Copyright 2020, Phys. Rev. Applied. b) Waveguide ENZ media for cross-talk reduction.[78] Licensed under the Creative Commons Attribution 4.0 International. c) Network impedance matching based on waveguide ENZ media.[79] Reproduced with permission. Copyright 2023, Nanophotonics.

optical effects have been realized, including perfect absorption, high-gain reflection without transmission, reflectionless high-gain transmission and reflectionless total transmission with different phases.

3.2. N-Port Network

As for other transmission applications, research have reported many microwave devices for various applications. ref. [78] introduces N-port equal/unequal-split power dividers based on waveguide ENZ media, as displayed in **Figure** 4a. An arbitrarily shaped waveguide ENZ media comprising a dielectric impurity is connected to N waveguides, and the incident power can be efficiently delivered to output waveguides. This design can further be extended to generic dividers with arbitrary power division ratios by modifying the widths of the output waveguides. ref. [79] demonstrates an ultra-compact waveguide systems. As displayed in Figure 4b, two dielectric waveguides are placed at a very narrow distance (e.g., $\lambda_0/30$, λ_0 is the free-space wavelength) on the substrate, which will introduce inevitable crosstalk for general cases. In this work, ENZ claddings are revealed, either isotropic or anisotropic, consequently prohibiting the crosstalk, bestowing ultra-compact waveguide systems. ref. [50] provides the potential of using waveguide ENZ media as lumped circuit elements. As shown in Figure 4c, a waveguide ENZ media comprising dielectric dopants is introduced within a transmission line to match a load of arbitrary complex impedance Z_L. By changing the sizes and permittivity of these dopants, any impedance can be realized to match different kinds of loads, including microwave circuits, antennas, and absorbing particles. In a short summary, waveguide ENZ media propose great potential of different transmission applications.

4. The Resonance of Waveguide ENZ Media

4.1. Quantum Emitters and Nonlinear Enhancement Devices

Waveguide ENZ media hold creative applications in resonator devices. In the optical frequency range, the near-field enhancement capability of waveguide ENZ media can be utilized to control local optical density of states, holding promise as a potent tool for future optical applications. Research has already demonstrated theoretically that ENZ media can achieve enhancement or suppression.[80] When electromagnetic waves impinge upon a 2D ENZ cylinder, the cylinder can generate two electric field hotspots and two electric field nodes around it, thereby enabling the enhancement or suppression of the optical field. When a small nonlinear particle approaches a subwavelength ENZ particle, the second harmonic generation (SHG) of the nonlinear particle can be markedly suppressed. This SHG quenching effect stems from the anomalous inhibition of the electric field near the ENZ particle due to the vanishing of scattered waves. Importantly, this phenomenon is universally observed in both isotropic and anisotropic ENZ particles, irrespective of their shapes.[71] The enhancement effect of waveguide effective ENZ is also calculated, as depicted in **Figure** 5a. Remarkable enhancement of the waveguide's local density of optical states (LDOS) is observed near the cutoff frequency. This phenomenon distinguishes from the plasmonic effects observed in metals within the optical regime;[37] instead, it emerges from the intrinsic structural properties of waveguide ENZ media, resulting in LDOS enhancement. The Rabi splitting of waveguide ENZ media integrated with internal nano particles is also discussed.[57] By integrating nanoscale metallic particles into waveguide ENZ media, a Rabi splitting of 300 meV can be observed. In addition, the spatiotemporal decoupling characteristics of waveguide ENZ media also offer advantages in optical devices. Ying Li et al. proposed a long-distance multi-qubit entanglement device based on waveguide ENZ media, as shown in Figure 5b.[81] Strong and uniform field enhancement is achieved at the ENZ resonance, resulting in effective transient entanglement among three randomly distributed quantum emitters along an elongated region in the plasmonic waveguide system. By leveraging the spatiotemporal decoupling properties of waveguide ENZ media, it is possible to extend the entanglement distance of quantum bits while achieving field enhancement in elongated regions. ref. [82] proposes a coiled cylindrical waveguide ENZ media demonstrating high-fidelity remote entanglement of embedded quantum bits, as illustrated in Figure 5c.

4.2. Signal Processing Devices

Based on the doping and spatiotemporal decoupling characteristics of ENZ media, we can manipulate the overall magnetic permeability of ENZ media through doping, achieving customized

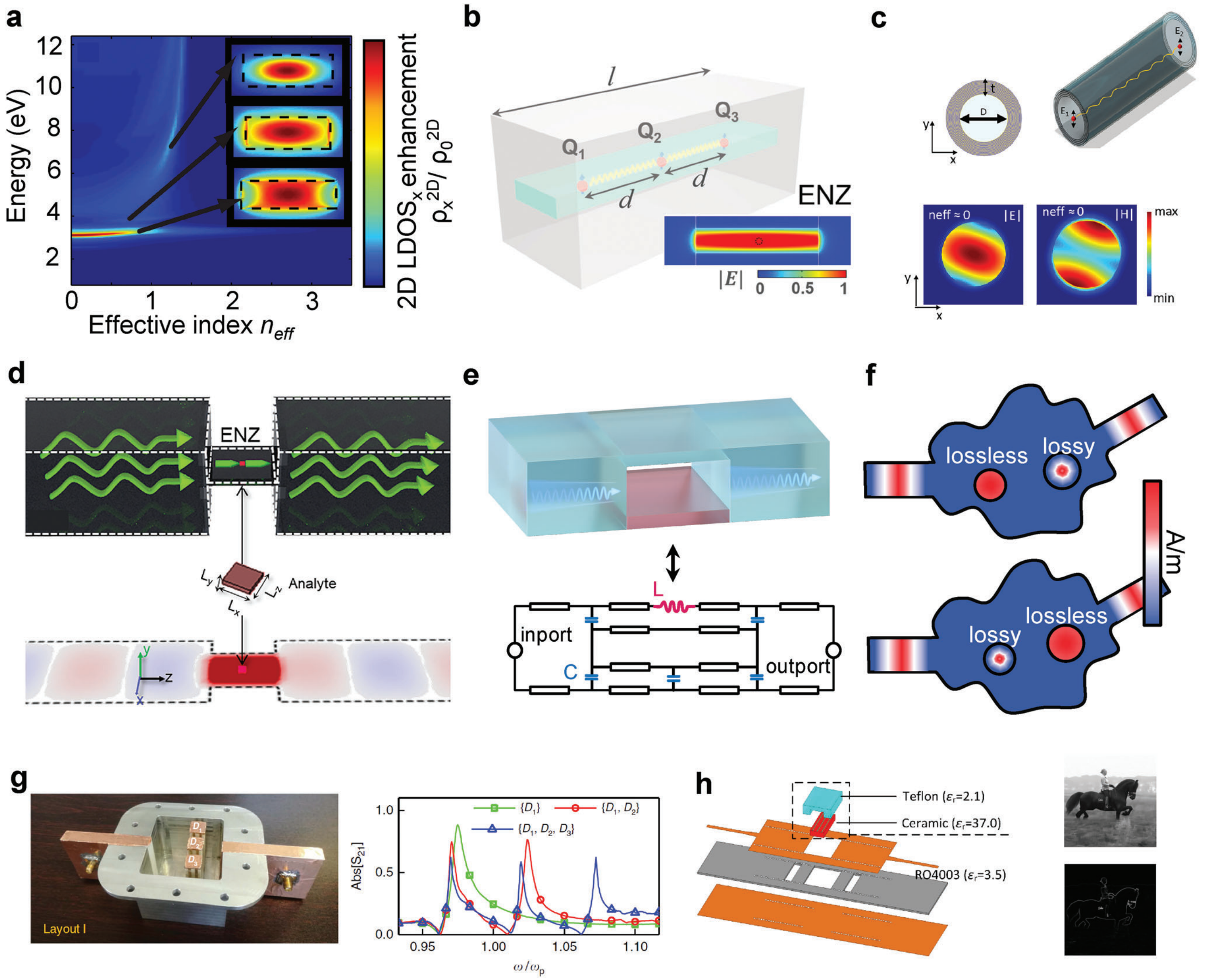

Figure 5. a) LDOS enhancement for waveguide ENZ media.[70] Licensed under the Creative Commons Attribution 4.0 International. b) Long-distance multi-qubit entanglement device based on waveguide ENZ media.[81] Licensed under the Creative Commons Attribution 4.0 International. c) Qubit entanglement in rolled-up waveguide ENZ media.[82] Reproduced with permission. Copyright 2021, Applied Physics Letters. d) Dielectric sensor based on waveguide ENZ media.[83] Licensed under the Creative Commons Attribution 4.0 International. e) Second-Order filter based on waveguide ENZ media.[84] f) Perfect coherent absorption based on waveguide ENZ media.[88] g) Dispersion coding of waveguide ENZ media via multiple photonic dopants.[58] Licensed under the Creative Commons Attribution 4.0 International. h) Performing calculus with waveguide ENZ media.[59] Licensed under the Creative Commons Attribution 4.0 International.

design of resonance points. Introducing multiple resonances enables various functionalities including sensing, filtering, encoding, and signal modulation. By discerning signal disparities between two waveguides, inversion of the optical parameters of objects within the ENZ cavity becomes feasible, thereby facilitating the production of deep subwavelength dielectric sensors.[83] As illustrated in Figure 5d, the object placed inside the ENZ cavity can be regarded as a new resonance point in the system. By analyzing the reflection and transmission signals of the waveguide, we can infer the permittivity of the object under test in a straightforward manner.

By designing multiple series or parallel ENZ cavities, it is possible to construct filters, as depicted in Figure 5e.[84] Several types of filters based on waveguide ENZ media have been discussed, including series-configured waveguide effective ENZ filters,[85] parallel-configured waveguide ENZ media filters,[84,86] and dual-band filters.[87] As discussed in Figure 2a, when dopants resonance occurs within ENZ media, the energy of the entire system becomes concentrated around the dopants. By introducing losses within the dopants, the magnetic permeability of the system can be adjusted to a purely imaginary number, thereby achieving perfect coherent absorption of electromagnetic waves,[88] as illustrated in Figure 5f. Furthermore, encoding structures based on waveguide ENZ media have also been investigated.

Figure 5g showcases a novel dispersion encoding configuration integrated with waveguide ENZ media, where photon dopants act as "bits" to program the spectral response of the entire composite medium.[58] This configuration retains the

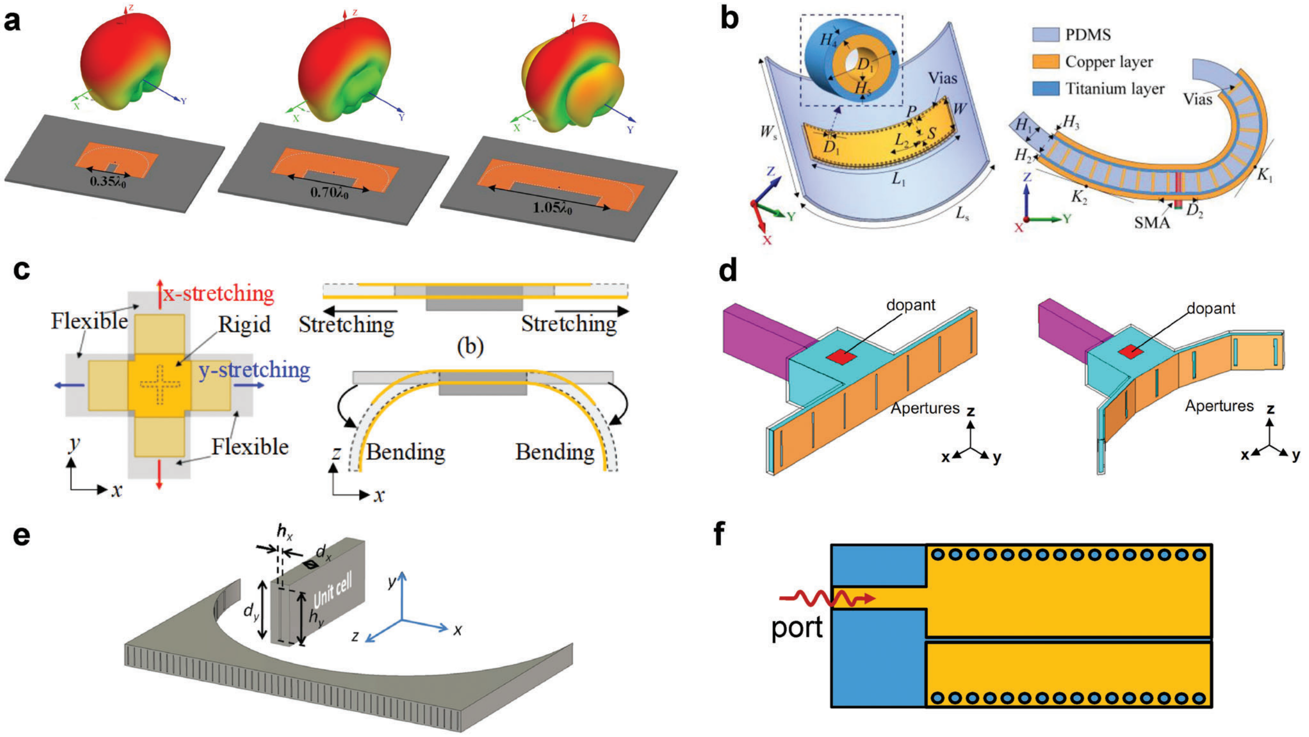

Figure 6. a) Size-independent antenna based on waveguide ENZ media.[11] Reproduced with permission. Copyright 2019, IEEE. b) Flexible Conformable Antenna.[12] Reproduced with permission. Copyright 2020, IEEE. c) Dual-Polarized antenna based on waveguide ENZ media.[97] Reproduced with permission. Copyright 2022, IEEE. d) Geometrically variable waveguide ENZ media antenna for wavefront control.[51] Licensed under the Creative Commons Attribution 4.0 International. e) Lensing system and fourier transformation based on waveguide ENZ media.[100] Copyright 2022, Phys. Rev. B. f) High-gain antenna based on waveguide ENZ media.[101]

size-decoupling characteristics of ENZ media, with the encoding frequency dependent solely on the dopants present, rather than being influenced by the shape of the waveguide ENZ media. Dispersion encoding has been proven to drive a range of innovative applications, including dynamically tunable comb-shaped dispersion profile filters and radio-frequency identification tags.[89] The unique dispersion of waveguide ENZ media after doping can also be applied in signal processing. Utilizing waveguide ENZ media, differential amplifiers can be designed. High-speed edge detection in images has been achieved through artificially designed resonances within waveguide ENZ media, as shown in Figure 5h.

5. The Radiation of Waveguide ENZ Media

Waveguide ENZ media has also found application in electromagnetic radiation. Benefitting from its spatially static wave dynamics, antennas based on waveguide ENZ media has exhibited two exotic features, namely geometry independency and beam synthesizing ability. Because of the near-infinite wavelength of the ENZ mode, the electric field performs a uniformed distribution inside the antenna.[90–93] Unlike typical antenna architectures,[94] altering the size of the antenna does not affect the field distribution, therefore having no effect on the operating frequency. Moreover, by opening radiation apertures along the waveguide ENZ media, the apertures share an in-phase and same-magnitude field, providing waveguide ENZ media antenna with beam synthesizing ability with high-gain or low-sidelobe performance.

5.1. Geometry-Independent Antenna

The concept of waveguide ENZ media antenna has been proposed in ref. [11], where an SIW waveguide operates at its ENZ mode, with two open ends as radiation apertures. The waveguide is fed with a coaxial probe. As derived, the operating frequency of the antenna yields $f_{\mathrm{ENZ}} = c/(2\sqrt{\varepsilon_r}W)$, where W is the effective width of the SIW waveguide. This derivation indicates that the operating frequency of the antenna is solely dependent on its width, while is independent from its length. As illustrated in **Figure 6a**, altering the length of the antenna changes its radiation pattern accordingly, while having no effect on its operating frequency. Moreover, it has been validated that antennas with bent waveguide also possess the identical feature of length-irrelevancy. To further validate the application scheme of the waveguide ENZ media antenna, a flexible waveguide ENZ media antenna is fabricated in ref. [12]. As illustrated in Figure 6b, an ENZ antenna based on SIW waveguide is printed on a flexible polydimethylsiloxane (PDMS) substrate. Antenna bent in different states are investigated in this work, validating its geometry robustness. This flexible ENZ antenna possesses application in wearable and biosensing systems. In ref. [95], an ENZ antenna based on bent waveguide is proposed for omnidirectional radiation. With the feeding probe, the effective magnetic current at the open ends direct reversely. For omnidirectional radiation, the waveguide is bent in a semicircular shape, aligning the two apertures. It is revealed that altering the radius of the waveguide solely effects the sidelobes, without deteriorating its omnidirectional radiation.

As discussed, the reversed magnetic current caused by the probe feeding method leads to a null point at the top of the radiation pattern. For a broadside radiation the feeding probe is replaced with a coupling slot in ref. [96]. The discontinuity at the slot causes an inversed electric field at different sides of the waveguide, therefore leading to in-phase magnetic current and a broadside beam. Further expanding the slot feeding structure, a dual-polarized waveguide ENZ media antenna is designed in ref. [97]. In this design, a crossed SIW waveguide is fed with a crossed slot, guaranteeing a dual-polarized performance as shown in Figure 6c. Simulation results validate that stretching or bending the waveguide at one direction independently affects the radiation pattern at this polarization. The concept of impedance matching for waveguide ENZ media with photonic doping has been proposed in refs. [14, 98, 99]. Applying this concept in waveguide ENZ media antennas, an antenna with photonic doping has been proposed in ref. [99]. Different from the previous ENZ antenna designs, the antenna applies a dielectric block in the waveguide as the dopant. With the dielectric dopant in the waveguide ENZ media antenna, the electric field of the antenna is inversed at different sides of the waveguide, creating a broadside radiation pattern. Because of the near-infinite wavelength inside the waveguide ENZ media, results indicate that the position of the dopant is insignificant in terms of its operation. The afore mentioned ENZ antenna designs are limited to a 1D geometry independency, i.e., length-irrelevancy. In ref. [51], the ENZ antenna is evolved into 2D geometry independency. As illustrated in Figure 6d, waveguide ENZ media antennas are constructed by opening radiation apertures on a cavity with metal walls. The cavity is fed with a waveguide, with photonic doping for impedance matching. It was theoretically derived in this work that the operating frequency of this antenna is dependent on the area of the cavity, without relevancy of its geometry. Therefore, it was experimentally demonstrated that the geometry of the antenna cavity independently defines the radiation pattern of the antenna. Antennas with different radiation patterns and directions can be realized through requirements.

5.2. High Gain Antenna

Beam synthesizing has been realized in multiple works with two major targets, namely high gain and low sidelobe. Utilizing the ENZ cavity model, an equivalent model can be built for the ENZ beam synthesizing antenna. The antenna can be modeled by a serial circuit fed with a voltage source, representing the feeding port. An inductor represents the ENZ cavity, whereas serial loads denote the radiation impedances of the ENZ antenna. Using the Kirchhoff's law, the voltage of the equivalent circuit yields

$$V_s = \sum_{n=1}^{N} V_n + j\omega L_{ENZ} I_0 \tag{6}$$

where V_s denotes the fed power and I_0 is the current along the ENZ waveguide. By altering the positions and impedances of the radiation impedances, beam synthesizing can be realized. In order for a high-gain radiation, a lens based on waveguide ENZ media was proposed in ref. [100]. As illustrated in Figure 6e, point source is placed in front of a circular lens built with waveguide ENZ media. Because of the infinite-wavelength propagation of the waveguide ENZ media, the output wave of the lens shares the same magnitude and phase, ensuring a high-gain performance. Utilizing the principle of waveguide ENZ media, a high-gain antenna based on waveguide ENZ media is proposed in ref. [101]. As shown in Figure 6f an SIW waveguide operating at its ENZ mode is fabricated with a slot etched longitudinally. According to the field distribution of the waveguide ENZ media, the slot possesses a uniform field distribution, therefore yielding a high gain. A high-gain horn antenna array is realized in ref. [102]. By utilizing multiple-feeding structure and aperture overlapping, a uniform field distribution is realized at the radiating aperture, forming an ENZ mode. Another major pursuit of beam synthesis is low sidelobe. In ref. [103], an antenna array with low sidelobe is realized. The array is realized by periodically etching radiating slots along a waveguide with closed ends. When the waveguide operates below the cutoff frequency, the wave resonant at an evanescent mode. A stepped field distribution is therefore formed, guaranteeing the low-sidelobe performance. Introducing microelectromechanical systems (MEMS) technology into this structure, a low sidelobe antenna array for on-chip application is realized in ref. [54]. The waveguide ENZ media medium ensures a low-sidelobe performance at 60 GHz millimeter wave. As a combination of the two pursuits, a 2D antenna array has been proposed in ref. [104]. According to the afore discussion, the waveguide antenna operates with a high-gain pattern at cutoff frequency, while possessing a low-sidelobe pattern below the cutoff frequency. The antenna array in ref. [104] combines the two operating modes into a wideband mode, possessing both low-sidelobe and high-gain performances.

6. Conclusion and Outlook

In recent years, significant achievements have been made in the understanding, discovery of interesting physical phenomena, experimental implementation, and device applications of waveguide ENZ media. Due to the disappearance of the real part of epsilon, many novel and unique properties of the fundamental interaction between light and matter have been revealed. These properties include the decoupling of spatiotemporal field changes, constant phase transmission, strong field confinement induced by boundary discontinuities, and nonlinear enhancement, yielding fascinating results. Further, a variety of inventive devices have been proposed, such as size-decoupled supercoupling, position-decoupled quantum near-field enhancement, arbitrary impedance matching and size-independent radiation structures. However, it is crucial to recognize that waveguide ENZ media still encounter two significant challenges that require attention: achieving wider bandwidth and reducing losses. The bandwidth of waveguide ENZ media remains relatively narrow due to limitations in waveguide dispersion, which restricts the potential applications of devices. Such high-Q structures are expected to enable high-sensitivity sensors, while realizing broadband devices is challenging. Additionally, addressing high losses is imperative. While waveguides, particularly air waveguides, demonstrate lower losses, unavoidable metal losses in the optical regime impede the further utilization of waveguide ENZ media.

In the future, new material breakthroughs, such as PEC in the optical band,[105,106] may solve the problems. It is anticipated that future technological advancements will enable waveguide ENZ media to achieve profound breakthroughs in photonics, communication, signal modulation, and other fields.

Acknowledgements

P.L., W.Y. and S.W. contributed equally to this work. This work was supported in part by the National Natural Science Foundation of China under Grant U22B2016, and the National Key Research and Development Program of China under Grant 2021YFA0716601.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

ENZ, metamaterial, waveguide dispersion, waveguide effective ENZ

Received: May 23, 2024
Revised: June 18, 2024
Published online: July 12, 2024

---

[1] J. Zhou, T. Koschny, L. Zhang, G. Tuttle, C. M. Soukoulis, *Appl. Phys. Lett.* **2006**, *88*, 221103.
[2] X. Niu, X. Hu, S. Chu, Q. Gong, *Adv. Opt. Mater.* **2018**, *6*, 1701292.
[3] B. Edwards, A. Alù, M. E. Young, M. Silveirinha, N. Engheta, *Phys. Rev. Lett.* **2008**, *100*, 033903.
[4] E. J. R. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman, *Phys. Rev. Lett.* **2013**, *110*, 013902.
[5] J. B. Pendry, D. Schurig, D. R. Smith, *Science* **2006**, *312*, 1780.
[6] A. Alù, N. Engheta, *Phys. Rev. E* **2005**, *72*, 016623.
[7] I. Liberal, A. M. Mahmoud, N. Engheta, *Nat. Commun.* **2016**, *7*, 10989.
[8] I. Liberal, N. Engheta, *Sci. Adv.* **2016**, *2*, e1600987.
[9] I. Liberal, N. Engheta, *Proc. Natl. Acad. Sci., U.S.A.* **2017**, *114*, 822.
[10] I. Liberal, N. Engheta, *Phys. Rev. A* **2018**, *97*, 022309.
[11] Z. Zhou, Y. Li, *IEEE Trans. Antennas Propagat.* **2019**, *67*, 2289.
[12] Z. Hu, C. Chen, Z. Zhou, Y. Li, *Antennas Wirel. Propag. Lett.* **2020**, *19*, 1591.
[13] M. Silveirinha, N. Engheta, *Phys. Rev. Lett.* **2006**, *97*, 157403.
[14] I. Liberal, A. M. Mahmoud, Y. Li, B. Edwards, N. Engheta, *Science* **2017**, *355*, 1058.
[15] Z. Zhou, Y. Li, H. Li, W. Sun, I. Liberal, N. Engheta, *Nat. Commun.* **2019**, *10*, 4132.
[16] S. Yin, E. Galiffi, A. Alù, *eLight* **2022**, *2*, 8.
[17] W. Yan, Z. Zhou, H. Li, Y. Li, *Nat. Commun.* **2023**, *14*, 6154.
[18] D. Yan, R. Mei, M. Li, Z. Ma, Z. H. Hang, J. Luo, *Nanophotonics* **2023**, *12*, 4195.
[19] Y. Wang, J. Lin, P. Xu, *Front. Phys.* **2024**, *19*, 33206.
[20] I. Liberal, N. Engheta, *Nature Photon* **2017**, *11*, 149.
[21] V. N. Tsytovich, *Sov. Phys. Uspekhi* **1967**, *9*, 805.
[22] J. Butet, P.-F. Brevet, O. J. F. Martin, *ACS Nano* **2015**, *9*, 10545.
[23] M. Soljačić, J. D. Joannopoulos, *Nat. Mater.* **2004**, *3*, 211.
[24] A. N. Poddubny, P. A. Belov, Y. S. Kivshar, *Phys. Rev. B* **2013**, *87*, 035136.
[25] M. Agio, D. M. Cano, *Nat. Photonics* **2013**, *7*, 674.
[26] A. E. Krasnok, A. P. Slobozhanyuk, C. R. Simovski, S. A. Tretyakov, A. N. Poddubny, A. E. Miroshnichenko, Y. S. Kivshar, P. A. Belov, *Sci. Rep.* **2015**, *5*, 12956.
[27] P. Li, P. Yu, J. Sun, Z. Jing, J. Wu, L. V. Besteiro, R. Caputo, A. Neogi, H. Xu, Z. Wang, *Photon. Res.* **2022**, *10*, 2178.
[28] P. B. Johnson, R. W. Christy, *Phys. Rev. B* **1972**, *6*, 4370.
[29] J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, *J. Phys.: Condens. Matter* **1998**, *10*, 4785.
[30] S. Enoch, G. Tayeb, P. Sabouroux, N. Guérin, P. Vincent, *Phys. Rev. Lett.* **2002**, *89*, 213902.
[31] V. Malka, P. Mora, *Comptes Rendus. Physique* **2009**, *10*, 106.
[32] Y. Liang, C. Li, Y.-Z. Huang, Q. Zhang, *ACS Nano* **2020**, *14*, 14375.
[33] S. Cho, Y. Yang, M. Soljačić, S. H. Yun, *Sci. Adv.* **2021**, *7*, eabf3362.
[34] S. Linic, S. Chavez, R. Elias, *Nat. Mater.* **2021**, *20*, 916.
[35] V. Jain, R. K. Kashyap, P. P. Pillai, *Adv. Opt. Mater.* **2022**, *10*, 2200463.
[36] O. Bitton, S. N. Gupta, G. Haran, *Nanophotonics* **2019**, *8*, 559.
[37] P. Li, P. Yu, W. Wang, F. Lin, H. Xu, Z. Wang, *J. Lightwave Technol.* **2021**, *39*, 7495.
[38] O. Bitton, G. Haran, *Acc. Chem. Res.* **2022**, *55*, 1659.
[39] D. C. Marinica, A. K. Kazansky, P. Nordlander, J. Aizpurua, A. G. Borisov, *Nano Lett.* **2012**, *12*, 1333.
[40] R. F. Ali, J. A. Busche, S. Kamal, D. J. Masiello, B. D. Gates, *Light: Sci. Appl.* **2023**, *12*, 99.
[41] I. Staude, J. Schilling, *Nat. Photonics* **2017**, *11*, 274.
[42] W. Li, F. Meng, Y. Chen, Y. fan Li, X. Huang, *Adv. Theory and Simul.* **2019**, *2*, 1900017.
[43] L. Li, H. Zhao, C. Liu, L. Li, T. J. Cui, *eLight* **2022**, *2*, 7.
[44] J. Deng, Y. Tang, S. Chen, K. Li, A. V. Zayats, G. Li, *Nano Lett.* **2020**, *20*, 5421.
[45] K. Pang, M. Z. Alam, Y. Zhou, C. Liu, O. Reshef, K. Manukyan, M. Voegtle, A. Pennathur, C. Tseng, X. Su, *Nano Lett.* **2021**, *21*, 5907.
[46] W. Rotman, *IRE Trans. Antennas Propag.* **1962**, *10*, 82.
[47] Y. Li, I. Liberal, C. Della Giovampaola, N. Engheta, *Sci. Adv.* **2016**, *2*, e1501790.
[48] M. G. Silveirinha, N. Engheta, *Phys. Rev. B* **2007**, *76*, 245109.
[49] Y. He, Y. Li, Z. Zhou, H. Li, Y. Hou, S. Liao, P. Chen, *Adv. Theory and Sims.* **2019**, *2*, 1900059.
[50] Z. Zhou, Y. Li, E. Nahvi, H. Li, Y. He, I. Liberal, N. Engheta, *Phys. Rev. Appl.* **2020**, *13*, 034005.
[51] H. Li, Z. Zhou, Y. He, W. Sun, Y. Li, I. Liberal, N. Engheta, *Nat. Commun.* **2022**, *13*, 3568.
[52] Y. Zhang, Y. Li, W. Zhang, Z. Zhang, Z. Feng, *Engineering* **2022**, *11*, 72.
[53] R. W. Ziolkowski, *Phys. Rev. E* **2004**, *70*, 046608.
[54] H. Li, Z. Zhou, Y. Zhao, Y. Li, *Chip* **2023**, *2*, 100049.
[55] A. Capretti, Y. Wang, N. Engheta, L. Dal Negro, *Opt. Lett.* **2015**, *40*, 1500.
[56] L. Caspani, R. P. M. Kaipurath, M. Clerici, M. Ferrera, T. Roger, J. Kim, N. Kinsey, M. Pietrzyk, A. Di Falco, V. M. Shalaev, *Phys. Rev. Lett.* **2016**, *116*, 233901.
[57] B. C. Yildiz, H. Caglayan, *Phys. Rev. B* **2020**, *102*, 165303.
[58] Z. Zhou, H. Li, W. Sun, Y. He, I. Liberal, N. Engheta, Z. Feng, Y. Li, *Light Sci. Appl.* **2022**, *11*, 207.
[59] H. Li, P. Fu, Z. Zhou, W. Sun, Y. Li, J. Wu, Q. Dai, *Sci. Adv.* **2022**, *8*, eabq6198.
[60] X. Qin, W. Sun, Z. Zhou, P. Fu, H. Li, Y. Li, *Nanophotonics* **2022**, *11*, 1659.
[61] M. Silveirinha, N. Engheta, *Phys. Rev. B* **2007**, *75*, 075119.
[62] A. M. Mahmoud, N. Engheta, *Nat. Commun.* **2014**, *5*, 5638.
[63] Y. Li, I. Liberal, N. Engheta, in *2017 Int. Conf. on Electromagnetics in Advanced Applications (ICEAA)*, IEEE, Piscataway, NJ **2017**, pp. 523–526.
[64] S. M. Sze, K. K. Ng, *Phys. semicond. Dev.* **2006**, *3*, 601.
[65] N. Engheta, R. W. Ziolkowski, *Metamaterials: Physics and Engineering Explorations*, John Wiley & Sons, Hoboken, NJ **2006**.

[66] G. V. Eleftheriades, K. G. Balmain, *Negative-Refraction Metamaterials: Fundamental Principles and Applications*, John Wiley & Sons, Hoboken, NJ **2005**.
[67] A. H. Sihvola, Electromagnetic Mixing Formulas and Applications, Iet, **1999**.
[68] S.-Y. Lee, K. Kim, S.-J. Kim, H. Park, K.-Y. Kim, B. Lee, *Optica* **2015**, *2*, 6.
[69] M. F. Imani, A. Grbic, *Antennas Wirel. Propag. Lett.* **2009**, *8*, 421.
[70] R. Sokhoyan, H. A. Atwater, *Opt. Express* **2013**, *21*, 32279.
[71] C. Wang, R. Shi, L. Gao, A. S. Shalin, J. Luo, *Photon. Res.* **2023**, *11*, 1437.
[72] R. Liu, Q. Cheng, T. Hand, J. J. Mock, T. J. Cui, S. A. Cummer, D. R. Smith, *Phys. Rev. Lett.* **2008**, *100*, 023903.
[73] W. Yan, Z. Zhou, H. Li, W. Sun, Q. Lv, Y. Li, *Laser Photonics Rev.* **2023**, *17*, 2201000.
[74] I. Liberal, M. Lobet, Y. Li, N. Engheta, *Proc. Natl. Acad. Sci., U.S.A.* **2020**, *117*, 24050.
[75] H. Li, Z. Zhou, W. Sun, M. Lobet, N. Engheta, I. Liberal, Y. Li, *Nat. Commun.* **2022**, *13*, 4747.
[76] X. Qin, Y. Li, *Phys. Rev. Applied* **2021**, *16*, 024033.
[77] B. Hong, L. Sun, W. Wang, Y. Qiu, N. Feng, D. Su, N. Somjit, I. Robertson, G. P. Wang, *Sci. China Phys. Mech. Astron.* **2022**, *65*, 274211.
[78] Z. Zhou, Y. Li, *IEEE Trans. Microwave Theory Techn.* **2021**, *69*, 1529.
[79] W. Ji, J. Luo, H. Chu, X. Zhou, X. Meng, R. Peng, M. Wang, Y. Lai, *Nanophotonics* **2023**, *12*, 2007.
[80] J. Song, J. Luo, Y. Lai, *Opt. Lett.* **2018**, *43*, 1738.
[81] Y. Li, C. Argyropoulos, *Appl. Phys. Lett.* **2021**, *119*, 211104.
[82] I. Issah, H. Caglayan, *Appl. Phys. Lett.* **2021**, *119*, 221103.
[83] M. Beruete, N. Engheta, V. Pacheco-Peña, *Appl. Phys. Lett.* **2022**, *120*, 081106.
[84] N. Vojnovic, B. Jokanovic, M. Radovanovic, F. Mesa, in *2015 9th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (METAMATERIALS)*, IEEE, Oxford, United Kingdom, **2015**, pp. 316–318.
[85] A. Corona-Chavez, D. V. B. Murthy, J. L. Olvera-Cervantes, *Micro & Optical Tech. Lett.* **2011**, *53*, 1706.
[86] N. Vojnovic, B. Jokanovic, M. Radovanovic, F. Medina, F. Mesa, *IEEE Trans. Antennas Propagat.* **2015**, *63*, 5107.
[87] M. Radovanovic, B. Jokanovic, *IEEE Microw. Wireless Compon. Lett.* **2017**, *27*, 554.
[88] W. Ji, D. Wang, S. Li, Y. Shang, W. Xiong, L. Zhang, J. Luo, *Appl. Phys. A* **2019**, *125*, 129.
[89] Z. Ziheng, L. I. Yue, *Chinese J. Radio Sci.* **2021**, *36*, 905.
[90] Y. Zhang, Y. Li, *IEEE Transactions on Antennas and Propagation* **2022**, *70*, 4215.
[91] Y. Zhang, Y. Li, *Sensors* **2022**, *22*, 788.
[92] Y. Zhang, Y. Li, *Electromag. Sci.* **2023**, *1*, 1.
[93] S. Wang, Y. Li, *IEEE Transactions on Antennas and Propagation* **2024**, *72*, 2391.
[94] M. Hu, Y. Li, Y. Zhang, P. Wu, H. Wang, *IEEE Antennas and Wireless Propagation Lett.* **2023**, *23*, 930.
[95] Z. Liu, Z. Zhou, Y. Li, Y. Li, *Appl. Phys. Lett.* **2021**, *119*, 151904.
[96] Z. Liu, Y. Zhang, W. Sun, Y. Li, *Antennas Wirel. Propag. Lett.* **2024**, 1.
[97] H. Li, Z. Zhou, Y. Li, *IEEE Trans. Antennas Propagat.* **2022**, *70*, 720.
[98] I. Liberal, Y. Li, N. Engheta, *Nanophotonics* **2018**, *7*, 1117.
[99] Z. Zhou, Y. Li, *IEEE Trans. Antennas Propagat.* **2020**, *68*, 5151.
[100] M. Navarro-Cía, M. Beruete, M. Sorolla, N. Engheta, *Phys. Rev. B* **2012**, *86*, 165130.
[101] D. M. George, A. Chandroth, C. C. H. Ng, P. R. Young, *J. Phys. D: Appl. Phys.* **2018**, *51*, 135102.
[102] H. Li, Y. Li, L. Chang, W. Sun, X. Qin, H. Wang, *IEEE Trans. Antennas Propagat.* **2021**, *69*, 815.
[103] H. Li, Y. Li, *IEEE Trans. Antennas Propagat.* **2022**, *70*, 11608.
[104] Y. Zhang, H. Li, Y. Zhao, Y. Li, *IEEE Trans. Antennas Propagat.* **2024**, *72*, 3055.
[105] S.-H. Kim, S. Kim, C.-S. Kee, *Phys. Rev. B* **2016**, *94*, 085118.
[106] Y. Zhou, X.-T. He, F.-L. Zhao, J.-W. Dong, *Opt. Lett.* **2016**, *41*, 2209.

Peihang Li received the B.S. degree in Shanxi University, Taiyuan, China, in 2020, and the M.S. degree in University of Electronic Science and Technology of China, Chengdu, China, where he is currently pursuing the Ph.D. degree in electronic engineering. His current research interests include terminal antennas, metamaterial antennas, epsilon-near-zero antennas.

Wendi Yan received the B.S. degree in electronic engineering from Tsinghua University, Beijing, China, in 2021, where he is currently pursuing the Ph.D. degree in electronic engineering. His current research interests include terminal antennas, metamaterial antennas, epsilon-near-zero antennas, and mu-near-zero antennas.

Shuyu Wang received the B.S. degree in electronic engineering from Tsinghua University, Beijing, China, in 2022, where he is currently pursuing the Ph.D. degree in electronic engineering. His current research interests include electrically small antennas, active circuits, and wideband active antennas.

Yue Li received the B.S. degree in telecommunication engineering from Zhejiang University, Hangzhou, Zhejiang, China, in 2007, and the Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China, in 2012, where he is currently an Assistant Professor and an Associate Professor with the Department of Electronic Engineering, Tsinghua University, Beijing, China. He is serving as an Associate Editor for IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, Microwave and Optical Technology Letters, and Computer Applications in Engineering Education. He is also serving on the Editorial Board of Scientific Reports, Sensors, and Electronics. His current research interests include metamaterials, plasmonics, electromagnetics, nanocircuits, mobile and handset antennas, MIMO and diversity antennas, and millimeter-wave antennas and arrays.