Research article

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Broadband dispersive free, large, and ultrafast nonlinear material platforms for photonics

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Abstract: Broadband dispersion free, large and ultrafast nonlinear material platforms comprise the essential foundation for the study of nonlinear optics, integrated optics, intense field optical physics, and quantum optics. Despite substantial research efforts, such material platforms have not been established up to now because of intrinsic contradictions between large nonlinear optical coefficient, broad operating bandwidth, and ultrafast response time. In this work, a broadband dispersion free, large and ultrafast

nonlinear material platform based on broadband epsilon-near-zero (ENZ) material is experimentally demonstrated, which is designed through a novel physical mechanism of combining structural dispersion and material dispersion. The broadband ENZ material is constructed of periodically nanostructured indium tin oxide (ITO) films, and the structure is designed with the help of theoretical predictions combined with algorithm optimization. Within the whole broad ENZ wavelength range (from 1300 to 1500 nm), a wavelength-independent and large average nonlinear refractive index of $-4.85 \times 10^{-11} \text{ cm}^2/\text{W}$, which is enlarged by around 20 times than that of an unstructured ITO film at its single ENZ wavelength, and an ultrafast response speed at the scale of Tbit/s are experimentally reached simultaneously. This work not only provides a new approach for constructing nonlinear optical materials but also lays the material foundation for the application of nanophotonics.

Keywords: all-optical tunability; broadband dispersion free nonlinear materials; epsilon-near-zero photonics; nonlinear metasurfaces; ultrafast photonics.

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1 Introduction

Nonlinear optical materials offer a platform for boosting the development of integrated optics, intense field optics, weak-light nonlinear optics, and quantum optics [1]. For practical applications, materials nonlinearity is expected to have the properties of broadband dispersion free, large, and ultrafast time response simultaneously [2]. However, most of natural materials have a relatively weak nonlinear optical response when operating away from resonances or suffer from strong nonlinear dispersions when operating on resonances [3, 4]. While the multicomponent organic materials and metal-dielectric composite materials have been proposed with enhanced the third-order nonlinearity, these enhancements rely deeply on the electronic resonances of materials themselves and thus result in degradations of response time and nonlinear bandwidth for practical use [5–12]. Therefore, the intrinsic contradictions among nonlinear coefficients, response time and nonlinear

bandwidth lie in the community of optical nonlinear materials and the practical utilizations are greatly impeded.

Epsilon-near-zero (ENZ) materials, i.e., optical materials with vanishing permittivities, have attracted substantial interest very recently as a new material system [13, 14]. The ENZ response exists widely and has been demonstrated in either natural materials or metamaterials at different spectral ranges [15–26]. Specifically to obtain ENZ responses in the optical communication range, the transparent conducting oxides such as indium tin oxide (ITO), aluminum-doped zinc oxide (AZO), and indium-doped cadmium oxide have advantages attributing to relatively high carrier concentrations [27–33]. It is exciting to explore the ENZ materials nonlinearities, since the electromagnetic field can be greatly enhanced due to the vanishing permittivity, which is free of resonance-related effects [34–36]. As a result, the field localization and subsequent nonlinearity enhancement do not slow down the ultrafast dynamic, i.e., the large nonlinear coefficient and ultrafast time response can be obtained simultaneously at the ENZ wavelength. However, all the existing ENZ materials present a single vanishing permittivity wavelength point in their dispersion relations, which causes the large and ultrafast nonlinear response is significantly restricted to a very narrow spectral range near the ENZ point, and becomes weakened rapidly at wavelengths away from the ENZ response [37, 38]. Recently, a strong coupling system, constructed by an ENZ film and gold nanoantenna resonators has been proposed, aiming to acquire broadband large nonlinearity around the single ENZ point [39]. While, the introduction of gold nanoantennas makes the resonant effect involved in this system, which has negative influences on the temporal dynamics of the system, resulting in a slower response time. These involved resonators also make the nonlinear dispersion dominated by the resonant lineshapes, therefore the acquired nonlinear coefficients are highly dispersive in this scheme. So far, the trade-offs of the materials' nonlinearity among the broadband dispersion free, large and ultrafast have not been overcome, and it is still a big challenge to acquire the desired nonlinear material systems with these properties simultaneously.

In this work, we go beyond the intrinsic contradictions and report a nonlinear material platform based on broadband ENZ materials with these properties simultaneously. The broadened ENZ response is acquired by our proposed dispersion engineering through the combination of structural dispersion and material dispersion. Specifically, the material platform is constructed by introducing a series of periodic composite nanostructure units into an ITO film, forming a verified broadband ENZ response ranging from 1300 to 1500 nm, which is in sharp contrast to the single-wavelength ENZ response of the unstructured ITO film. The optical linear

transmission properties including amplitude and phase changes were characterized to demonstrate the average value of the real part of permittivity is 0.083 in the 200-nm-wide ENZ range. We demonstrate the strong nonlinear optical response of this ENZ platform are wavelength-independent, with an average nonlinear refractive index of $-4.85 \times 10^{-11} \text{ cm}^2/\text{W}$ (normal incidence) within the whole 200-nm-wide ENZ range, which is about five orders of magnitude larger than that of the silica substrate and around 20 times larger than that of an unstructured ITO film at its ENZ wavelength. Thanks to the nonresonant nonlinearity enhancement mechanism, our broadband ENZ material maintains the ultrafast recovery time of the host film of ITO, which is about 400 fs in our case. Based on the excellent nonlinear properties of dispersion free, large, ultrafast temporal response and the materials technology compatibility, our build-up broadband ENZ system eliminates the long-standing nonlinearity constraints and offers an ideal material platform for boosting the research of integrated optics, intense field optics, weak-light nonlinear optics, and quantum optics in photonics community.

2 Results and discussion

2.1 Theoretical prediction

The periodic subwavelength-scale nanostructures (Figure 1A) were patterned in an ITO film for engineering the dispersion of the system, based on the electromagnetic field homogenization theory [40]. The designed structures are constructed by periodically repeating a basic block consisting of four subwavelength-scale composite units with the same thickness but different ITO filling ratios, ρ_i . In the theory of effective medium, each composite unit with a certain filling factor can be regarded as an ITO-air layered homogenized medium. In our case, the first unit was selected to be an unpatterned ITO layer without air, where the permittivity was the ITO's permittivity itself. The second and third units were composed of air and partially etched ITO with different heights. The fourth unit was a layer of pure air, i.e., the ITO was removed completely. The dispersion relation of each composite unit is adjustable by varying the filling ratios of ITO. Considering the subwavelength layer thickness, the effective permittivity ε_i of each composite unit can be described by geometrically averaging and written into [41]

$$\varepsilon_i = \rho_i \varepsilon_{\text{ITO}} + (1 - \rho_i) \varepsilon_{\text{air}} \quad (1)$$

where ρ_i is the ITO filling ratio of each composite unit, ε_{air} is the permittivity of air, and ε_{ITO} is the permittivity of ITO film. The measured ε_{ITO} using variable-angle spectroscopic ellipsometry is displayed in Figure 1B, which shows clearly

the single ENZ wavelength of 1265 nm for the unstructured ITO film. By introducing the air layer into the ITO film, the ENZ wavelength of the composite unit can be tuned. As shown in Figure 1C, the effective ENZ wavelengths are spectrally red-shifted to 1330 and 1505 nm with ITO filling ratios ρ_i of 0.4 and 0.7 respectively, indicating the tunability of such shiftings by varying the ρ_i . Subsequently, combining the units of pure ITO, composite layers of ITO and air with different filling factors, and pure air (which has a positive permittivity in the designed ENZ spectral range), the effective permittivity ϵ_{eff} of the system (also the basic block), are homogenized further, followed by

$$\epsilon_{\text{eff}} = \left(\sum_i (\epsilon_i d_i)^{-1} \right)^{-1} \quad (2)$$

where d_i represents the duty ratio of each composite unit to every basic block, and ϵ_i is the effective permittivity of each composite unit. According to Eq. (2), the designed system

owns vanishing permittivity as long as one of the composite units presents a vanishing permittivity. And the dispersion relation among these points can be engineered by properly selecting the duty ratios d_i of each composite unit. Therefore, through choosing the structural parameters including d_i and ρ_i , a material system with a flattened dispersion and a broadband ENZ response can be obtained. In Figure 1D we displayed the theoretically predicted dispersion relation, and the broadband ENZ response is seen (also see Supplementary material).

2.2 Algorithm optimization for practical structural parameters

However, the utilized effective medium theory (EMT) can precisely predict the electromagnetic response of the nanostructures only if the period approaches to zero. As the

Figure 1: Optical constants of the ENZ material.

(A) Schematic of the multicomposite subwavelength nanostructures inscribed in the indium tin oxide (ITO) films (w_i and h_i are geometrical dimensions of the composite units). Light is incident along the y -direction and polarized along the x -direction. (B) Measured real (ϵ_1 , blue line) and imaginary (ϵ_2 , red line) permittivity of the ITO film. (C) Calculated real part of permittivity for effective ENZ points in the ITO-air homogenized nanostructures with different ITO filling ratios. (D) Theoretically predicted effective permittivity of the basic block in the designed composite ENZ material based on effective medium theory. (E) Calculated effective permittivity of the designed ENZ material. The algorithm optimization has been considered, and the broadband ENZ response is obtained from 1300 to 1500 nm.

increasing of the practical period, the deviations between the theoretical predictions and the practical responses will be enlarged owing to the nonlocal effect [42]. On the other hand, the finite number of layers also results in deviation from theoretical predictions, since based on the EMT, the number of layers is set to be infinity [43]. Limited by the precision of nanofabrication technology, these limitations make the broadband ENZ response cannot be experimentally reached guided by the theoretical predictions purely [40]. To solve this problem, we developed an optimization strategy based on the genetic algorithm combined with the finite element method, and this optimization is aimed to determine the realistic structural parameters with consideration of the deviations from the theoretical model mentioned above [44]. Based on the method, the theoretical predictions are chose as initial populations and the optimization is conducted with considering the practical nonzero period and finite thickness and layer numbers in each unit. Specifically, in our case, the period was set to be 400 nm and the thickness is fixed to be 200 nm to meet the practical fabrication aspect, respectively. It is also worth mentioning that in this method, the optimization step can be controlled to meet the practical fabrication accuracy, which is also vital for experimental realization (see Figure S1 and S2 in Supplementary material). According to our calculations, the weight of each practical composite unit, w_1 , w_2 , w_3 , and w_4 , were 120, 40, 80, and 160 nm, respectively. While the height of the ITO in the four composite units, h_1 , h_2 , h_3 , and h_4 , were 200, 100, 80, and 0 nm, respectively. The calculated effective permittivity of the designed dispersion-flattened broadband ENZ composite periodic nanostructure is shown in Figure 1E, by using the widely used homogenization procedure [45]. The broadband ENZ response presents in the wavelength range from 1300 to 1500 nm.

2.3 Sample fabrication and linear characterization

For the fabrication of the dispersion-engineered broadband ENZ sample, we utilized the focused ion beam (FIB) milling technique (Helios Nanolab 600i, FEI Company) to etch the periodic nanostructures in a 200-nm-thick ITO film. The ITO film was deposited on silica substrates by magnetron sputtering (LAB18, Kurt J. Lesker Corp.). The thickness of 200 nm was chosen to make the measured results clearly and convinced. The all-dielectric configurations ensure the designed dispersion-engineered nanostructures to be compatible with the complementary metal–oxide–semiconductor process, and it can also be

manufactured with the standard semiconductor fabrication technology including electron beam lithography (EBL) combined with dry etching. It is also worth mentioning that the usage of EBL and dry etching can be helpful to fabricate the sample with large size. The top-view scanning electron micrograph (SEM) of the sample is shown in Figure 2A in a size of $30 \times 30 \mu\text{m}$. The subwavelength structure with a period of 400 nm is clearly visible in the magnified image (Figure 2B). For experimental measurements, we also etched reference substrates by removing the ITO within the same geometrical dimensions. The incident light was set to be x-polarized.

The linear optical properties of the dispersion-engineered ENZ nanostructures were characterized by measuring the transmission spectrum at normal incidence. The transmission spectrum was also simulated by using the finite element method (COMSOL Multiphysics). The real dimensions of the periodic unit cells obtained from the SEM images of the fabricated sample and the experimentally measured permittivity of the ITO and silica substrate were used in the simulations. Owing to the subwavelength dimension of the building blocks, the incident light is transmitted perpendicularly to the sample. Both of the measured and simulated results are shown in Figure 2C. It is seen the measured transmission gradually decreases at longer wavelengths, which agrees well with the simulations. There are no distinct dips in the transmission spectrum, indicating that the fabricated nanostructures do not involve any resonance. The slight difference between the experimental and simulation results may originate from the redeposition of ITO and Ga^+ ions injecting phenomena during the FIB milling process. The normalized transmittance is around 0.3 in the designed ENZ window (from 1300 to 1500 nm, as marked between the two dashed lines in Figure 2C). To reveal the physical origins of the transmission loss, we measured the transmittance ratios of the nanostructured ENZ sample to an unstructured ITO film with same thickness (Figure 2D). The ENZ sample exhibits approximately 0.8 of the ratio to the unstructured film, demonstrating the inherent loss of the ITO material being the major reason for the low transmission of the ENZ sample. Another factor may be related to the dispersion modifications. The flattened dispersion curves in the broadband ENZ region could be regarded as a type of abnormal dispersion phenomenon, which can also induce unneglectable absorption.

The ENZ response of the dispersion-engineered sample was also characterized by measuring the phase change of the transmitted light. For this purpose, the white-light interference based on a specially designed Mach–Zehnder interferometer was used to record three sets of interference

Figure 2: Scanning electron micrograph (SEM) images and optical characteristics of the broadband ENZ response.

SEM top-view (A) and magnified (B) images of the structure. The sample is a 30 μm × 30 μm rectangle and the period is 400 nm. (C) Measured and simulated transmission spectrum of the fabricated ENZ sample. (D) Measured and simulated transmission ratio between the nanostructured ENZ sample and the pure ITO film on the same substrate. (E) Measured normalized interference patterns formed through the light transmitted through the ENZ sample, air hole and ITO film combined with the light transmitted through the reference arm by utilizing the white-light interference, respectively. (F) Extracted phase change of the light transmitting through the ENZ sample, air hole and bare ITO film, respectively. (G) Measured and retrieved effective permittivity for the ENZ material sample. The broadband ENZ response is obtained from 1300 to 1500 nm.

patterns in wavelength domain, where a supercontinuum laser source (SC-PRO, YSL Photonics Co.) was utilized (also see Figure S6 and S7 in Supplementary material), and the experimental results are shown in Figure 2E. The three sets of interference patterns are formed between the ENZ sample and a reference substrate, an unstructured ITO film and a reference substrate, and two reference substrates,

respectively. According to the shifts of these interference patterns, the phase shift of the light transmitted through the ENZ sample, and also the sample's optical length was derived. Specifically, the normalized intensity $I_{r,s,ITO}$ can be expressed as

$$I_{r,s,ITO} = \cos(\varphi_{\text{initial}} + \varphi_{r,s,ITO}) \quad (3)$$

where the subscripts r , s , and ITO represent the reference substrate, the ENZ sample, and the unstructured ITO film, respectively. φ_{initial} represents the initial phase difference between the two optical paths. And $\varphi_{r,s,\text{ITO}}$ can be substituted with $\varphi_r = k_0 d$, $\varphi_s = k_0 n_{\text{eff}} d$, $\varphi_{\text{ITO}} = k_0 n_{\text{ITO}} d$, in which k_0 , d , n_{eff} and n_{ITO} are the free space wave vector, the thickness of the ENZ sample, the real part of effective refractive index, and the real part of ITO's refractive index, respectively. Since the thickness of the sample is only 200 nm, much less than the vacuum wavelength in the measured wavelength range, the orders of the interference patterns are the same in the three situations. Then the phase change of the light passing through the ENZ sample can be described

$$\varphi_s = \cos^{-1}(I_s) - \cos^{-1}(I_r) + \varphi_r \quad (4)$$

The fitted phase changes are shown in Figure 2F, and also shown are the simulated results (the blue lines) and the retrieved phase changes of unstructured ITO (the black lines). A good agreement between the experimental and simulations results is established. Compared with the unstructured ITO, the ENZ sample exhibits a flattened phase change characteristic in the wavelength window of 1300 to 1500 nm, indicating a strong modified dispersion response in this range. To retrieve the homogenized effective permittivity from the measured transmission and phase shift, a transfer matrix method was applied (see Figure S8 in Supplementary material for details), and the results are shown in Figure 2G. The broadband ENZ response is determined, which ranges from 1300 to 1500 nm, with a bandwidth of 200 nm and an averaged value of 0.083 for the real part of permittivity.

2.4 Nonlinear characterization

To characterize the nonlinear optical response of the broadband ENZ sample, we performed a series of Z-scan measurements with laser wavelengths varied from 1250 to 1650 nm at normal incidence [46]. In this low index medium, the measurements are used to extract the change of refractive index Δn with injected pump pulse, which value represents the strength of optical nonlinearity [47]. The incident intensity was maintained at 48 GW/cm² for all the wavelengths, lower than the damage threshold of ITO [27, 48]. For bare ITO films, the nonlinearity is originated from the nonequilibrium distributions of the free carriers, and the nonlinear refractive index shows a positive value [25]. While in our designed sample, similar to the linear dispersion, the nonlinear dispersion is also determined by the combination of material dispersion and structural

dispersion. Therefore, the sign of nonlinear refractive index of our sample is no longer constrained by the ITO's n_2 and can be switched by structural design. For illustrating the strength of the nonlinearity to compare with other nonlinear materials clearly, the absolute value of the nonlinear refractive index $|n_2|$ is used to characterize the nonlinearity of the ENZ sample. This value is obtained through the absolute value of refractive index change $|\Delta n|$ according to the expression $|n_2| = |\Delta n|/I$. As shown in Figure 3A, broadband-flattened, i.e., dispersion free, nonlinearity is obtained in the whole ENZ spectral range. The measured maximal and minimal $|n_2|$ values are 5.63×10^{-11} and 4.30×10^{-11} cm²/W, respectively. The average measured $|n_2|$ in the ENZ range is around 4.85×10^{-11} cm²/W, which is five orders of magnitude larger than that of the silica substrate and around 20 times larger than that of the ITO film without structural modifications at the same normal incident conditions [27, 49]. This value also illustrate that the value of Δn is larger than unity in this 200-nm-wide band. As a result, our proposed material system not only leads to a broadband ENZ response, but also enables dispersion free and large nonlinearity in this region. This merit is beneficial to satisfy the requirement of broadband operation bandwidth with ultralow energy consumptions of the optical applications in a wide photonics community.

The broadband and nondispersive nonlinearity enhancement can be understood by considering the following two factors. The first one is the electric field enhancement, which physically results from the displacement field continuity in the ENZ system. The calculated electric field enhancement factors at different incident angles is shown in Figure 3B, which illustrate the ratios of the electric field intensity in the ENZ sample to the incident intensity. With the utilization of structural dispersion, our platform provides distinct field enhancement properties compared to original ENZ film. For the entire ENZ region from 1300 to 1500 nm, the electric fields undergo distinct enhancements, with the maximum factor around 6.5 at the angle with normal incidence. In contrast, the maximum field enhancement factor appears only at a tilt incidence for the natural ENZ films, while for normal incidence, the field cannot be coupled into [27]. This also contributes to orders of magnitude nonlinearity enlargement of our platform compared to the bare ITO film. The other reason is the increased absorption due to the abnormal dispersion of the broadband ENZ system. As shown in Figure 3C, the fabricated sample undergoes an increased and wavelength-flattened absorption in this ENZ range.

The nonlinear dynamics of our broadband ENZ system is primarily dominated by the nonlinear response of host

Figure 3: Nonlinear properties of the designed ENZ material. (A) Measured absolute value of nonlinear refractive index of the ENZ material. The ENZ material shows a dispersion free nonlinearity enhancement at the broadband ENZ region. (B) Calculated intensity enhancement factors as functions of wavelength and incident angle. The ENZ material exhibits a wideband field enhancement at normal incidence. (C) Retrieved absorption coefficient of the ENZ material. The absorptions are unneglectable in the broadband ENZ region. (D) Pump-induced change in the transmittance of the probe at 1300 nm. Dashed vertical lines represent the 90–10% recovery time. The ultrafast recovery time is dictated by the electron–phonon coupling strength of the intraband transition free carriers.

material, ITO. The sample's measured temporal dynamics of the nonlinear response (Figure 3D) indicates a rise time of 160 fs and a recovery time of 400 fs, which was tested through a degenerate pump–probe measurement system at the wavelength of 1300 nm with a Ti:sapphire laser system (Legend Elite, Coherent). The rise time is mainly determined by the temporal width of the incident pump pulse, suggesting an onset of nonlinear response with sub-100 fs dynamics. The ultrafast recovery time of 400 fs can be attributed to the intraband transitions of the free carriers in the conduction band of ITO and also the nonresonant properties of the sample. The fs-scale response time indicates the proposed broadband ENZ material have potentials to realizing all-optical signal processing devices with a speed of several Tbit/s.

2.5 Discussion

Looking beyond the fabricated sample, our proposed principle, i.e., EMT theory combined with genetic algorithm optimizations, is also able to design the broadband ENZ response in different spectral range based on different structures and materials, indicating a broad applicability in material community. Without replacing the ITO, the spectral locations of the broadband ENZ response can be designed with tunability (as shown in Figure 4A). Through varying geometrical parameters, the broadband ENZ response with a fixed bandwidth of 150 nm can be shown at

the wavelength range of (1350, 1500 nm), (1450, 1600 nm), and (1550, 1700 nm), respectively, which cover the generally used E, C, and L bands in optical communication. Increasing the number of units in our adopted composite nanostructures, the bandwidth of the ENZ response can be enlarged further. In a system with similar composite nanostructures containing six units on an ITO film, the ENZ response can be designed from 1500 to 2000 nm with an enlarged bandwidth of 500 nm (Figure 4B). In addition to ITO, the method also has the wide-range material compatibility. The AZO material is another type of transparent conducting oxides, with a natural ENZ response at the near-infrared range [30]. Introducing the composite nanostructures we designed into this host material, the broadband ENZ response can be constructed within a range from 1500 to 1700 nm, as displayed in Figure 4C. The proposed principle and method are also suitable to be adopted into other types of materials such as titanium nitride, where the broadband ENZ response can be built up in the visible range. Naturally, the titanium nitride shows the ENZ response at 487 nm [50], and after the structural modifications, the ENZ response can be broadened ranging from 600 to 700 nm, as shown in Figure 4D.

Thanks to the physical mechanism of effective permittivity homogenization and the developed algorithm optimization, the broadband ENZ response can be reached in the sample with different thickness on demand based on our design method. As a result, it has potential to be applied in variety scenes. In addition, for further reducing

Figure 4: General applicability of the developed design method for acquiring broadband ENZ response. (A) Effective permittivity spectra of the composite nanostructures designed on the ITO film. The range with broadband ENZ can be shown at (1350, 1500 nm), (1450, 1600 nm), and (1550, 1700 nm), respectively (covering the generally used E, C, and L band in optical telecom spectral range). (B) The ENZ spectral range can be enlarged ranging from 1550 to 2000 nm through the similar structure. (C) The calculated effective permittivity of AZO film with nanostructures by our method. The broadband ENZ response is located from 1500 to 1700 nm. (D) The broadband ENZ response at visible range is calculated to be reached by dispersion engineering on TiN film.

the inherent losses, it is also feasible to consider losses optimization with the structural dispersion engineering to obtain a low-loss broadband ENZ material platform [51].

3 Conclusions

In conclusion, the long-standing obstacles for simultaneous acquisition of broadband dispersion free, large, and ultrafast nonlinearity have been eliminated through our broadband ENZ material platform via dispersion engineering approach. We have fabricated a proof-of-concept sample composed of subwavelength nanostructures in a 200-nm-thick ITO film. The fully characterized transmission properties confirm a broadband ENZ response from 1300 to 1500 nm. The ENZ sample was verified to show large and broadband-flattened nonlinear coefficients, as well as ultrafast time response. The average absolute value of the nonlinear refractive index is determined to be $4.85 \times 10^{-11} \text{ cm}^2/\text{W}$ across the entire 200-nm-wide ENZ range, which is about five orders of magnitude larger than that of the conventionally used silica glasses and around 20 times enhancement compared with the unstructured materials. The recovery time of this nonlinear material is determined to be 400 fs, corresponding to a processing speed rate of exceeding 1 Tbit/s. These performances illustrate the dispersion engineering through the combination of the structural dispersion and material dispersion

can effectively modify the linear and nonlinear permittivity of optical materials simultaneously. Our proposed strategy for material design possesses the extensive applicability, and it is not only suitable for ENZ materials but also for constructing nonlinear organic polymers, semiconductors, and oxides. The broadband ENZ materials we provide with broadband dispersion free, large, and ultrafast nonlinearity will become a vital platform for promoting the research studies in integrated optics, intense field optics, weak-light nonlinear optics, and quantum optics in a wide photonics community.

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