1. Introduction

Epsilon-Near-Zero (ENZ) materials are characterized by a vanishingly small permittivity ($\varepsilon$) obtained over a narrow spectral region, also known as the ENZ region. Ideally, when $\varepsilon \to 0$ the wavelength of light within the ENZ medium approaches infinity, its group velocity tends to zero, and the normal component of the transverse magnetic (TM) polarized light experiences a large enhancement.\([1-3]\) As a result of these unconventional optical properties, interesting optical phenomena such as wave tunneling,\([4]\) directional emission,\([5]\) frequency conversion,\([6-8]\) intensity-dependent refraction,\([9-15]\) and frequency translation due to time-varying refractive index\([16]\) have been realized in ENZ materials. A well-known class of ENZ media includes transparent conducting oxides (TCOs) such as indium–tin oxide (ITO),\([9]\) aluminum-zinc oxide (AZO),\([10]\) and indium–cadmium oxide (ICO).\([11]\) These are n-type semiconductors with a free-electron density on the order of $10^{28}$ cm$^{-3}$. The near-zero permittivity of these materials is obtained at the zero-crossing wavelength ($\lambda_{ZC}$) where the real part of the complex permittivity becomes zero. Some advantages of TCOs over other ENZ media are their tunable optical properties in the near-infrared (NIR) region of the spectrum, a straightforward fabrication, and a large optical damage threshold. Due to these advantages, significant effort has been dedicated to characterizing their linear and nonlinear optical responses\([6,9-12,15,18]\) as well as optimizing the optical properties by tailoring the material parameters.\([19-22]\)

Theoretical and experimental studies of the optical response of TCOs in the ENZ region have reported a perfect absorption of TM-polarized light\([15,17,18]\) and an increased conversion efficiency of the nonlinear processes such as harmonic generation.\([6-8]\) Moreover, an ultrafast and large nonlinear change of refractive index ($\Delta n$) has been demonstrated for these materials.\([9-12,14]\) which makes them potential candidates for applications in all-optical data processing and telecommunication. The large values of $\Delta n$ are caused by an increase in the effective mass of free electrons due to an intraband excitation in the non-parabolic conduction band of TCOs.\([9,11,12,14]\) Several studies have also achieved significant improvement in the optical response of TCOs by fabricating ENZ-plasmonic structures, taking the advantage of strong coupling between the resonance of plasmonic nanostructure and the ENZ mode of the ultrathin TCO film.\([23-25]\) Research has been also performed on tuning the optical properties of TCOs in the ENZ region.

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adom.202201748.

© 2022 The Authors. Advanced Optical Materials published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

DOI: 10.1002/adom.202201748
by manipulating the materials parameters. For instance, one can widely tune the $\lambda_{2C}$ of TCOs by adjusting the free-electron density during fabrication or post-deposition annealing.\cite{19-21} Recently, we have evaluated the impact of crystal quality of ITO and showed that the optical loss and free-electron effective mass are reduced in highly-crystalline thin films.\cite{22} We also showed that the figure of merit proposed for intraband nonlinearities\cite{26} is larger for ITO films of high crystal quality. Similar experimental results showing an increase in $\Delta n$ for ITO films with preferential crystal orientation have been also reported.\cite{27}

The nonlinear optical properties of TCO-based ENZ materials have attracted much attention recently, in part because of the large and ultrafast intensity-dependent refraction phenomenon exhibited by these materials. Despite the large interest in this subject, little information has been given on the bandwidth of the nonlinear response and its dependence on intensity. Moreover, only the well-known TCOs have been examined giving less attention to other TCOs such as indium–zirconium oxide (IZrO) and lanthanum–barium stannate, which have been recently investigated as alternative high mobility transparent electrodes.\cite{28-30} Therefore, it would be a valuable effort to explore new TCO materials that could offer improved optical properties such as a wide ENZ region. Such a feature could enable strong optical interactions over a broad spectral range, which in turn could help to expand the ENZ-TCO functionalities into more application areas. Widening the ENZ spectral region can be accomplished by developing multilayered TCO films composed of layers with different $\lambda_{2C}$.\cite{31,32} Also, ENZ-plasmonic structures have been reported to achieve improved optical response over a broad spectral range.\cite{34,35} Nonetheless, fabricating these structures can be challenging; hence, investigating TCO films that could offer a wider ENZ region in a single layer form is important.

In this work, we report the spectrally broad nonlinear optical response of a polycrystalline IZrO film in the ENZ spectral region. The film exhibits an optically-induced nonlinear change in transmittance with estimated full-width-at-half-maximum (FWHM) bandwidth as large as 260 nm corresponding to the wavelength range of 1488–1747 nm, covering the entire spectral range of the C, L, and U optical telecommunication bands. Further optical and compositional characterizations suggest that the broadband nonlinear response is caused by a spatially graded near-zero permittivity along the direction of the film thickness. Moreover, we report for the first time the linear optical properties of IZrO in the ENZ region. Measurements show that IZrO is a low loss TCO, having an imaginary part of the permittivity that is 56% and 20% smaller with respect to those reported for AZO\cite{21} and ITO,\cite{19} respectively, for a comparable thickness and $\lambda_{2C}$. The reduced optical loss is beneficial for a number of optical phenomena such as directive emission, perfect absorption, and frequency conversion.

2. Linear Optical Properties of the IZrO Films

Figure 1a illustrates schematically the thin film structures used for our investigation, which consists of an IZrO film with subnanometer surface roughness (Figure 1b) and thickness $d$ deposited on a glass substrate. Similar to other TCOs, the complex permittivity of IZrO in the NIR region of the spectrum can be approximated by the Drude model:\cite{33}

$$\varepsilon(\omega) = \text{Re}(\varepsilon) + i\text{Im}(\varepsilon) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$

with

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m^*}}$$

$$\gamma = \frac{\varepsilon}{m^* \mu_{opt}}$$

where $\varepsilon_\infty$ is the high-frequency permittivity, $\omega_p$ is the plasma frequency, and $\gamma$ is the damping constant. $N_e$, $m^*$, and $\mu_{opt}$ represent the free-electron density, effective mass, and optical mobility, respectively. Equation (2) and (3) indicate the importance of material parameters in controlling the optical properties of the TCO films, which as mentioned earlier, is an advantage of these ENZ media over others.

The main material parameters affecting the strength of the linear and nonlinear optical interactions are $N_e$, $m^*$, $\mu_{opt}$, and $\varepsilon_\infty$. We obtain the value of $N_e$ through Hall effect measurements. To collect the other parameters we first retrieve the
permittivity data, shown in Figure 2a by solid circles, by fitting the spectroscopic ellipsometry (SE) spectra to a combination of Tauc-Lorentz and Drude oscillators assuming a homogeneous IZrO layer. The permittivity data is then fitted to a Drude model (dashed lines in Figure 2a) using a nonlinear least-squares minimization method to extract $\varepsilon_\infty$, $\omega_p$, and $\gamma$. Finally, the obtained values of $N_e$, $\omega_p$, and $\gamma$ are used to calculate the values of $m^*$ and $\mu_{\text{opt}}$ from Equation (2) and (3), respectively.

The results listed in Table 1 show that $\mu_e$ is significantly higher for the thicker samples compared to the 36 nm film. The increase of $\mu_e$ with the thickness was previously studied in Ref. [29]. The authors point to ionized impurity scattering as the main scattering mechanism in IZrO films and found that ionized impurity scattering had a larger contribution to transport in thinner films, likely caused by a larger density of surface defects. On the contrary, as shown in Table 1, $\mu_{\text{opt}}$ doesn’t show a thickness dependence. This indicates that grain boundary scattering might also influence intra-grain scattering ($\mu_e$), but not $\mu_{\text{opt}}$ as this is only limited by in-grain scattering sources. Here, the fabricated IZrO films have similar values of $N_e$ and hence quite similar values of $\mu_{\text{opt}}$ (65–74 cm$^2$ V$^{-1}$ s$^{-1}$), being comparable to those reported for highly-crystalline ITO films.[22] The values of $m^*$ obtained for the IZrO films are in the range of 0.26–0.29 $m_0$, which are smaller than the typical values (0.35–0.43 $m_0$) reported for polycrystalline ITO$^{[34–36]}$ at similar $\lambda_{\text{ZC}}$. The main optical properties affected by the material parameters are $\lambda_{\text{ZC}}$ and the corresponding $\varepsilon_{\text{Im}}$. As summarized in Table 1, $\lambda_{\text{ZC}}$ is practically the same for all IZrO films. However, $\varepsilon_{\text{Im}}$ reduces for the thicker films caused by a reduction in $\gamma$ due to an increase in the product $m^*\mu_{\text{opt}}$ (see Equation (3)). The $\varepsilon_{\text{Im}}$ values obtained for the IZrO films are 20% and 56% smaller than those reported for ITO and AZO, respectively.$^{[19,21,34]}

We also carry out further SE analyses to study the possible variations in the optical properties along the thickness of the IZrO films and evaluate the effect of such variations on the optical properties of the IZrO samples.

| d [nm] | $N_e$ [$\times 10^{20} \text{ cm}^{-3}$] | $\mu_e$ [cm$^2$ V$^{-1}$ s$^{-1}$] | $\mu_{\text{opt}}$ [cm$^2$ V$^{-1}$ s$^{-1}$] | $m^*/m_0$ | $\varepsilon_{\text{Im}}$ | $\lambda_{\text{ZC}}$ [nm] | $\varepsilon_{\text{Im}}$ | $\omega_p/\gamma$ |
|-------|--------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
| 36    | 4.8                           | 24.3            | 65.2 ± 0.3      | 0.26            | 4.6             | 1681            | 0.42            | 23.42          |
| 59    | 4.8                           | 73              | 66.7 ± 0.1      | 0.28            | 4.3             | 1680            | 0.37            | 24.82          |
| 114   | 4.7                           | 71              | 74.1 ± 0.1      | 0.29            | 4               | 1675            | 0.3             | 27.52          |
width of the ENZ spectral region. To this end, the SE spectra are fitted using a graded layer model, which divides the TCO film into multiple slices that could have different properties and provides a $\lambda_{zc}$ for each slice. Such a model improves the fit to SE spectra of the IZrO films, compared to the case of the homogeneous layer model; the mean-squared-error of the fit improves by 10%, 39%, and 35% for the 36 nm, 59 nm, and 114 nm films, respectively. Figure 2b illustrates the best fit results for the 114 nm IZrO sample that is composed of 20 slices, showing different wavelength-dependent permittivity values for the top and bottom slices (also see Figure 2c). Noteworthy, the top slice has a shorter $\lambda_{zc}$ than the bottom one, leading to a 115 nm spectral width for the ENZ region. Similar results are also obtained for the 36 and 59 nm IZrO films (Figure S1, Supporting Information).

The graded optical properties along the thickness of the TCO films, also studied by others [27,37,38] can have different origins (or a combination of effects) such as nonuniform composition or dopant distribution, varying density or microstructure, and different types of defects. For instance, graded permittivity due to the nonuniform distribution of free electrons in ITO and inhomogeneous microstructure in AZO has been reported using SE analyses in Refs. [37, 38]. Based on previous work on IZrO and further characterization of the films, the possible causes of the gradient can be linked to: i) a larger density of defects at the substrate/IZrO film interface, as suggested by Rutherford Backscattering (RBS) measurements. The RBS results show that In/Zr ratios measured at 2 and 5 MeV are not in agreement within the measurement accuracy (see Section S2, Supporting Information). Reasons for the discrepancy could be a nonuniform Zr depth profile in the film or a profile interference with a trace component in the glass substrate, e.g., Barium Oxide.

The position-dependent variation of the IZrO film’s permittivity along the $z$ coordinate has a dramatic influence on the electric field distribution within the material. This is because the $z$-component of the electric field inside the material with the permittivity of $\varepsilon$ is related to that of the incident electric field by $E_{in,z} = E_0 z (\varepsilon_0/\varepsilon)$, where $\varepsilon_0$ is the permittivity of the region from which light is incident onto the structure; hence, for oblique illumination, a larger field intensity enhancement (FIE), $|E_{en}/E_0|^2$, develops in those regions where $\varepsilon$ approaches zero. Consider for instance the 114 nm IZrO film discussed before. Figure 3 shows numerical calculations of the position and wavelength-dependent FIE in the films. The results in Figure 3a,b are calculated by taking the homogeneous permittivity presented in Figure 2a, while those in Figure 3c,d are calculated using a permittivity that varies linearly along the $z$-axis according to measurements in Figure 2b. Figure 3a,c[b,d] corresponds to the case of illumination from the air (substrate) region. Note that for the inhomogeneous IZrO film, the FIE is larger and more tightly localized to specific regions in the film where the permittivity approaches zero.

The reduction in free-electron density along the thickness would also affect the other material parameters of the IZrO layer; for instance, $m^*$ will decrease along the $z$ axis. This, together with the more localized field enhancement, would result in position-dependent nonlinear interactions within the IZrO film.[22,26]

3. Nonlinear Optical Response

Figure 4a,b illustrates the wavelength and intensity-dependent nonlinear change of transmission ($\Delta T$) for the 114 nm IZrO film measured using TM-polarized light incident onto the sample (see Figure 1) from the air side and the substrate side, respectively. The incident light is a pulsed laser beam with a temporal width of $\approx$70 fs at the sample location (see Experimental Section). The laser beam is weakly focused, and its intensity is controlled to generate values in the range of 15 to 100 GW cm$^{-2}$ at the surface of the sample. Since the field intensity in an ENZ material is enhanced for TM-polarized oblique illumination, leading to an enhancement of its nonlinear optical response, our measurements are performed at an incidence angle of $\theta = 50^\circ$ (see Section S3, Supporting Information). The results show that $\Delta T$ does not change significantly over the measured wavelength range. We have extracted the FWHM values of $\Delta T$ (Figure 4b,c) by fitting the experimental data to a combination of two Gaussian functions (see Section S4, Supporting Information), since the variation in $\Delta T$ with wavelength is not symmetric and hence the fit to a single Gaussian function does not describe the expected shape of the $\Delta T$ spectrum. These results, summarized in Table 2, show that FWHM varies between 138 and 260 nm for the case of illumination from the substrate side; similar results are obtained when light is incident from the air region. It is worth mentioning that even at the lowest intensity (15 GW cm$^{-2}$) the obtained bandwidth covers the spectral range for the C, U, and L telecommunication bands combined.

The observed broadband nonlinear response could be partly due to the large spectral bandwidth (FWHM = 45 nm) of the light source used for the measurements. However, the extracted values of FWHM for $\Delta T$ are significantly larger than that of the laser pulse, suggesting a different broadening mechanism. We attribute the broadband response of $\Delta T$ to the wide ENZ spectral region of the IZrO films resulting from a varying permittivity along the thickness of the film. Contrary to the linear case, where light experiences an average permittivity as it propagates through the film, our nonlinear measurements are sensitive to the local permittivity within the film. As mentioned earlier, this is because the electric field inside the film is enhanced more significantly in those regions where $\varepsilon$ approaches zero (see Figure 3b,c), leading to a spectral nonlinear response that is correlated to the spatial distribution of $\varepsilon$ at $\lambda_{zc}$. Furthermore, an overestimation of the nonlinear change in transmittance through Transfer Matrix Method calculations using an intensity-dependent Drude model for the homogeneous IZrO film shows that $\Delta T$ is not expected to have the large bandwidth observed experimentally (see Section S5, Supporting Information); this, in turn, further supports the impact of graded permittivity on the measured broadband $\Delta T$.

Figure 5a,b shows the normalized nonlinear change in transmittance, $\Delta T/\Delta T_{max}$ for light incident onto the structure from
the air side and from the substrate side, respectively. Here, ΔT_{max} is the maximum nonlinear change in transmittance at a given intensity obtained over a wavelength range that is within the ENZ spectral region (1625 – 1740 nm) in Figure 2b. These results show that when light is incident from the air with the lowest intensity, the normalized response at λ = 1690 nm drops by ≈70% compared to that at 1630 nm. This means that the material’s nonlinear response is larger in the region near the air/IZrO interface than for the substrate/IZrO interface. Similar results are obtained when the structure is illuminated from the substrate side. Considering that the FIE is expected to be similar over the entire wavelength range of 1620 – 1690 nm (below the dashed lines in Figure 3c,d) for both illumination configurations, the results in Figure 5a,b suggest that the graded permittivity steps near to the substrate/IZrO interface are thinner than those near the air/IZrO interface. This, in turn, leads to shorter interaction lengths and consequently smaller ΔT values at longer wavelengths.

Figure 5a,b also shows an increase in the normalized response at longer wavelengths as a function of intensity, which results in a flatter spectrum for larger intensities. This is because the rate of increase in ΔT versus I at higher intensities is larger for the longer wavelengths compared to the shorter ones, as shown in Figure 5c,d. Moreover, at a given wavelength, the nonlinear response saturates at lower intensities for the case of illumination from the substrate region because a larger FIE is generated in such a configuration (see Figure 3d).

4. Discussion and Conclusion

Our measurements show that IZrO is a low-loss TCO, which would make it a good choice for applications based on near-zero index photonics. For instance, one could further reduce the thickness required for a perfect absorption of TM-polarized light, as it is proportional to \( \varepsilon_{\text{Im}}() \). A less restrictive phase matching enabled by the smaller refractive index of IZrO would also increase the conversion efficiency of harmonic generation.\(^{[6]}\) Moreover, the small \( m^0 \) values would be beneficial for the intensity-dependent refractive index.\(^{[22,26]}\)

The observations made in this work concerning the graded permittivity and the broadband nonlinear response of a TCO have not been previously reported. Nonetheless, in one instance (Ref. [10]) we note that the bandwidth of ΔT of the 900 nm-thick AZO film studied can have similar values to those reported here (FWHM = 225 nm for 435 GW cm\(^{-2}\) and FWHM = 185 nm for 870 GW cm\(^{-2}\)). This suggests that the film studied in Ref. [10] could possess a graded permittivity as well. Our observations, however, occur for much thinner films and at significantly lower optical intensities, which could arise from a steeper gradient in the optical properties along the thickness of IZrO films.

In conclusion, we reported for the first time the linear optical properties and nonlinear optical response of IZrO thin films in the near-zero permittivity region. It is shown that IZrO has high optical mobility leading to its considerably small optical loss;
Im(ε) as low as 0.3 is obtained. It is also shown through SE analyses that the IZrO films have a graded permittivity and a broadening of the ENZ spectral region. This gradient could result from substrate/IZrO interface defects, a strain gradient, and/or nonuniform dopant distribution. The variation in the permittivity along the thickness would not affect the linear optical response, as this type of response depends on the permittivity that is averaged over the entire thickness of the film. However, the nonuniform permittivity distribution would have an impact on the nonlinear optical response because the nonlinear interactions are position-dependent and, hence, are affected by the spatial distribution of the permittivity. Our measurements reveal that the graded optical properties of the IZrO films result in a broadband nonlinear change in transmission with a FWHM reaching ≈ 260 nm. Such a bandwidth covers more than the whole spectral range for the three consecutive C, L, and U telecommunication bands. Finally, the nonlinear measurements under different configurations along with the FIE calculations suggested a reduction in the width of the graded permittivity steps (thickness of slices) from the top to the bottom of the IZrO film.

5. Experimental Section

IZrO Films Fabrication: The IZrO films were deposited on glass substrates following the procedure described in detail elsewhere. In short, the films were fabricated at room temperature using a Pulsed
Laser Deposition system (Twente Solid State Technologies B.V.). Glass substrates were ultrasonicated in acetone and isopropanol for 5 min and rinsed in deionized water before deposition. A KrF excimer laser ($\lambda = 248$ nm) was used for all experiments with an optimized repetition rate of 20 Hz and a laser fluence of $1.9 \text{ cm}^2/\text{J}$. The total working pressure was 0.02 mbar with an optimized $\text{Ar}/\text{O}_2$ ratio of 4:1. The as-deposited IZrO films were subsequently annealed in the ambient environment at 200 °C for 20 min to achieve polycrystalline IZrO films via solid-phase crystallization.

Characterization of the Material Properties: Quantitative elemental analyses were performed by RBS using 2 and 5 MeV He ions and a silicon PIN diode detector under 168° (Laboratory of Ion Beam Physics at the Swiss Federal Institute of Technology Zurich). Linear permittivity was collected by SE measurements using a J.A. Woollam M-2000UI ellipsometer at three angles (65°, 70°, and 75°) in the wavelength range of 246–1688 nm. Surface roughness was measured by Atomic Force Microscopy (AFM) using a Bruker Icon Dimension in Tapping mode. Room temperature free-electron density ($N_e$) and electrical mobility ($\mu$) were measured using Hall effect measurements in the van der Pauw configuration.

Nonlinear Measurements: Wavelength-dependent nonlinear change of transmission $\Delta T = T - T_0$, with $T_0$ ($T$) being the linear (nonlinear) transmittance, was measured at different light intensities and an incidence angle of 50°. The samples were illuminated by TM-polarized laser pulses with tunable center wavelength generated by a Ti:Sapphire regenerative amplifier (Coherent Legend) followed by an optical parametric amplifier (Coherent Opera). The Signal (Idler) part of the output with a 5 kHz repetition rate was used for measurements in the wavelength range of 1500–1590 nm (1620–1690 nm). The wavelength-dependent pulse duration was in the range of 57–88 fs, as measured by an autocorrelator.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
H.G. is grateful to CONACYT for the financial support under the scholarship 971961. H.G. also acknowledges the support from the
University of Twente, the Netherlands for funding this research. I.D.L. acknowledges the support of CONACyT (Ciencia Básica) under grant number 286150. Y.S and M.M.M. acknowledge the support from Dr. Max Doebeli at ETH Zürich for the RBS measurements on the IZrO films.

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
broadband nonlinear response, epsilon-near-zero, graded permittivity, indium oxide, indium-zirconium oxide, transparent conducting oxides

Received: July 27, 2022
Revised: September 12, 2022
Published online: October 13, 2022

[1] N. Engheta, Science 2013, 340, 286.
[2] S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, F. Capolino, Phys. Rev. B 2013, 87, 035120.
[3] H. Gobadi, Z. Jafari, I. D. Leon, in Plasmon-enhanced light-matter interactions, Springer, Cham, Switzerland 2022, pp. 27–55.
[4] M. Silveirinha, N. Engheta, Phys. Rev. Lett 2006, 97, 157403.
[5] S. Enoch, G. Tayeb, P. Sabouroux, N. Guérin, P. Vincent, Phys. Rev. Lett 2002, 89, 213902.
[6] A. Capretti, Y. Wang, N. Engheta, L. Dal Negro, ACS Photonics 2015, 2, 1584.
[7] T. S. Luk, D. De Ceglia, S. Liu, G. A. Keeler, R. P. Prasankumar, M. A. Vincenti, M. Scalora, M. B. Sinclair, S. Campione, Appl. Phys. Lett. 2015, 106, 151103.
[8] Y. Yang, J. Lu, A. Manjavacas, T. S. Luk, H. Liu, K. Kelley, J.-P. Maria, E. L. Runnerstrom, M. B. Sinclair, S. Chimire, I. Brener, Nat. Phys. 2019, 15, 1022.
[9] M. Z. Alam, I. De Leon, R. W. Boyd, Science 2016, 352, 795.
[10] L. Caspani, R. Kaipurath, M. Clerici, M. Ferrera, T. Roger, J. Kim, N. Kinsey, M. Pietrzyk, A. Di Falco, V. M. Shalaev, A. Boltasseva, D. Faccio, Phys. Rev. Lett 2016, 116, 233901.
[11] P. Guo, R. D. Schaller, J. B. Kettersson, R. P. Chang, Nat. Photonics 2016, 10, 267.
[12] Q. Guo, Y. Cui, Y. Yao, Y. Ye, Y. Yang, X. Liu, S. Zhang, X. Liu, J. Qiu, H. Hosono, Adv. Mater. 2017, 29, 1700754.
[13] Y. U. Lee, E. Garoni, H. Kita, K. Kamada, B. H. Woo, Y. C. Jun, S. M. Chae, H. J. Kim, K. J. Lee, S. Yoon, E. Choi, F. Mathevet, I. Ozerov, J. C. Ribierre, J. W. Wu, A. D’Alélo, Adv. Opt. Mater. 2018, 6, 1701400.
[14] H. Wang, K. Du, C. Jiang, Z. Yang, L. Ren, W. Zhang, S. J. Chua, T. Mei, Phys. Rev. Appl. 2019, 11, 064062.
[15] Y. Yang, K. Kelley, E. Sachet, S. Campione, T. S. Luk, J.-P. Maria, M. B. Sinclair, I. Brener, Nat. Photonics 2017, 11, 390.
[16] Y. Zhou, M. Z. Alam, M. Karimi, J. Upham, O. Reshef, C. Liu, A. E. Willner, R. W. Boyd, Nat. Commun. 2020, 11, 2180.
[17] T. S. Luk, S. Campione, I. Kim, S. Feng, Y. C. Jun, S. Liu, J. B. Wright, I. Brener, P. B. Catrysse, S. Fan, M. B. Sinclair, Phys. Rev. B 2014, 90, 085411.
[18] D. G. Baranov, A. Krasnok, T. Shegai, A. Alù, Y. Chong, Nat. Rev. Mater. 2017, 2, 17064.
[19] Y. Wang, A. Capretti, L. Dal Negro, Opt. Mater. Express 2015, 5, 2415.
[20] S. Xian, L. Nie, J. Qin, T. Kang, C. Li, J. Xie, L. Deng, L. Bi, Opt. Express 2019, 27, 28618.
[21] S. Gurung, A. Anopchenko, S. Bej, J. Joyner, J. D. Myers, J. Frantz, H. W. H. Lee, Adv. Mater. Interfaces 2020, 7, 2000844.
[22] H. Gobadi, Y. Smirnov, H. L. Offerhaus, J. A. Alvarez-Chavez, M. Morales-Masis, I. De Leon, Opt. Mater. Express 2022, 12, 96.
[23] S. Campione, J. R. Wendt, G. A. Keeler, T. S. Luk, ACS Photonics 2016, 3, 293.
[24] J. R. Hendrickson, S. Vangala, C. Dass, R. Gibson, J. Goldsmith, K. Leedy, D. E. Walker Jr, J. W. Cleary, W. Kim, J. Guo, ACS Photonics 2018, 5, 776.
[25] M. Z. Alam, S. A. Schulz, J. Upham, I. De Leon, R. W. Boyd, Nat. Photonics 2018, 12, 79.
[26] R. Secondo, J. Khurgin, N. Kinsey, Opt. Mater. Express 2020, 10, 1545.
[27] W. A. Britton, F. Sgrignuoli, L. Dal Negro, Appl. Phys. Lett. 2022, 101901, 12090.
[28] Y. Smirnov, L. Schmengler, R. Kuik, P.-A. Repecaud, M. Najafi, D. Zhang, M. Theelen, A. Aydin, S. Veenstra, S. De Wolf, M. Morales-Masis, Adv. Mater. Technol. 2021, 6, 2000856.
[29] E. Rucavado, F. Landucci, M. Dobeli, Q. Jeangros, M. Boccard, A. Hessler-Wyser, C. Ballif, M. Morales-Masis, Phys. Rev. Mater. 2019, 3, 084608.
[30] Y. Smirnov, J. Holovsky, G. Rijnders, M. Morales-Masis, APL Mater. 2020, 8, 061108.
[31] J. Yoon, M. Zhou, M. Badsha, T. Y. Kim, Y. C. Jun, C. K. Hwangbo, Sci. Rep. 2015, 5, 12788.
[32] K. P. Kelley, E. L. Runnerstrom, E. Sachet, C. T. Shelton, E. D. Grimley, A. Klump, J. M. LeBeau, Z. Sitar, J. Y. Suen, M. L. Brongersma, Appl. Phys. Lett. 2014, 105, 181117.
[33] Y. Gui, M. Miscuglio, Z. Ma, M. H. Tahersima, S. Sun, R. Amin, H. Dalir, V. J. Sorger, Sci. Rep. 2019, 9, 11279.
[34] M. Losurdo, K. Hingerl, Ellipsometry at the Nanoscale, Springer, Berlin, Germany 2013.
[35] D. Zhitina, Y. Smirnov, P.-A. Repecaud, L. A. B. Marcal, G. Fevola, D. Sheyfer, G. A. Keeler, M. B. Sinclair, I. Brener, Nat. Commun. 2019, 10, 2180.
[36] J. Wallentine, M. Morales-Masis, M. E. Stuckelberger, Commun. Mater. 2022, 3, 38.