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Three wave mixing in epsilon-near-zero plasmonic waveguides for signal regeneration

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ABSTRACT

Vast improvements in communications technology are possible if the conversion of digital information from optical to electric and back can be removed. Plasmonic devices offer one solution due to optical computing's potential for increased bandwidth, which would enable increased throughput and enhanced security. Plasmonic devices have small footprints and interface with electronics easily, but these potential improvements are offset by the large device footprints of conventional signal regeneration schemes, since surface plasmon polaritons (SPPs) are incredibly lossy. As such, there is a need for novel regeneration schemes. The continuous, uniform, and unambiguous digital information encoding method is phase-shift-keying (PSK), so we chose to focus on developing a regeneration scheme compatible with PSK. Epsilon-near-zero (ENZ) materials have been shown to support SPP modes and have extremely high conversion rates for harmonic generation at their zero-permittivity wavelength, which makes them particularly desirable for developing signal regeneration devices. We have shown second-harmonic generation (SHG) in free space with simulations consisting of ENZ materials. When integrated into plasmonic waveguides, SHG can be used to conduct phase sensitive amplification (PSA), which allows us to combine phase-squeezing and amplification into a single stage instead of relying on conventional gain media for amplification. PSA can be utilized to design a proof-of-concept signal regeneration device with a smaller overall device footprint than previously demonstrated methods. The development of these methods will contribute towards minimizing device footprints of plasmonic components that require signal regeneration, improving their density and performance.

Keywords: Optical computing, signal regeneration, phase-shift-keying, epsilon-near-zero materials, second-harmonic generation, phase sensitive amplification, phase squeezing

INTRODUCTION

Optical Computing

Separate from the field of electronic computing, using electricity to drive logic elements, is optical computing, where instead photons drive logic elements. Optical signals are already being used for telecommunications in the form of fiber-optic cable, since they are much more efficient for long distance data transfer than conventional electrical cable[1]. Optical signals also tend to be more efficient for bulk computations due to the parallelism possible by using multibit symbols, but their effectiveness is often limited by the availability of functional optical logic elements. Optical logic devices generally must be designed holistically instead of from building blocks, in contrast to electronic logic devices, which can take advantage of hierarchy and modularity in their design. This introduces the optical-electronic-optical (o-e-o) problem; the lack of fully optical circuits necessitates certain computations necessary in a communication link be performed with electronic signals, requiring any signal to be transformed from optical to electronic and back again to perform those tasks. The transition from optical to electronic and electronic to optical is computationally expensive and significantly slows down optical systems[1]. The removal of these optical-electronic-optical conversions would allow for vast technological improvements in communications technology. Devices utilizing optical signals have increased bandwidth, which ultimately could provide increased throughput and enhanced security. This increased bandwidth is generally provided by utilizing multibit symbols with quadrature amplitude modulation or phase-shift-keying (PSK), with an arbitrarily high number of states per symbol, limited by the quality of signal regeneration, among other things [1]. In particular, PSK encodes the data of the signal into the phase of the light, and unlike other alternatives like quadrature amplitude modulation, PSK is continuous, uniform, and unambiguous, making it an attractive encoding scheme for various optical logic implementations[1].

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Signal regeneration

Regardless of the encoding, signal regeneration is necessary when transmitting data over large distances, as without it the signal dies out over time and noise accumulates and obfuscates the original signal. Signal regeneration consists of two main elements: quantization and amplification. Signal quantization is the process used to remove noise based on the expected values, while signal amplification is the process used to increase the amplitude of the signal so it can travel larger distances. However, signal regeneration (particularly quantization) is one of the tasks that is currently done with electronic signals; it is one of the biggest contributors to the negative impact of the o-e-o problem, particularly because optical signals are being relied upon for communications over long distances. Optical signals deteriorate during transmission, so it is imperative to have an effective signal regeneration scheme to ensure that data is not lost in transit. This is even more important for multibit symbol encoding schemes. There is a need for a novel, all-optical signal regeneration scheme to nullify the o-e-o problem in the most common use case for optical signals and to allow for full utilization of optical signals' increased bandwidth[2,3]. Phase sensitive amplification is commonly used in research to regenerate a signal encoded with phase-shift keying, by selectively targeting and amplifying only expected phase values, and it can be achieved with a second-order nonlinear effect known as second-harmonic generation (SHG)[1].

Epsilon-Near-Zero materials

Epsilon-Near-Zero (ENZ) materials support plasmonic modes under certain conditions, and have high conversation rates for harmonic generation[4–7]. There are still unanswered questions when it comes to ENZ materials, but it is widely accepted that ENZ materials exhibit second-order nonlinear effects on optical signals near their zero-permittivity wavelength. Most notably, these materials have been used for SHG[8], an effect that can be used to achieve the aforementioned phase-sensitive amplification. They have other benefits, such as negating the phase-matching condition necessary for most nonlinear interactions, since near a zero index all waves will have the same phase[7,9]. Of the known ENZ materials, indium tin oxide, aluminum zinc oxide, and gallium zinc oxide are good material candidates due to their zero-permittivity wavelengths, and we choose to focus on indium tin oxide (ITO) due to its prevalence in conventional semiconductor manufacturing and its commercial availability. Additionally, it has been shown that the ENZ wavelength of commercially available ITO can be easily tuned using a simple annealing technique[10,11]. The unique properties of ENZ materials will allow us to maintain a smaller device footprint than conventional methods, all while avoiding the o-e-o problem and permitting us to take advantage of optical signals' potential for increased bandwidth.

METHODS

Simulations

To simulate the nonlinear phenomena, we use ANSYS Lumerical FDTD, an optical simulation software that solves meshed regions at discrete time steps. We validated our simulation geometry with a custom material profile for an arbitrary nonexistent material with an unusually high value for $\chi^{(2)}$ to verify the ability to generate and measure the sought after second-order nonlinear phenomena. Subsequently we set up a custom material profile for ITO, given known refractive indices at various wavelengths[12], and a measured value for $\chi^{(2)}$. The value for $\chi^{(2)}$ we used is 1.8 $1.8\times 10^{-13} mV^{-1}$, which represents a best-case scenario depending on the orientation of the ITO material[4]. Depending on the needs of the particular simulation, a thin-film indium tin oxide was placed, various plane waves were emitted towards it, and the optical power per wavelength was measured and recorded using field time monitors. Using these simulations, we verified our nonlinear model for ITO was working properly.

In addition to the free-space simulations, we set up multiple simulations with ITO and plasmonic waveguide structures. While our initial goal was to use a dielectric-loaded surface-plasmon polariton (DLSPP) configuration, with the ITO acting as the metal substrate, we quickly ran into issues. The most important issue is that, although ITO can support plasmonic modes near the zero-permittivity wavelength, at shorter wavelengths (like the second-harmonic), it exhibits dielectric behavior and no longer supports this mode[13,14]. Therefore, we could not effectively generate second-harmonic signals in this configuration.

To adapt to this problem, we decided to use a plasmonic slot waveguide configuration. In this configuration, we used two gold layers 300 nm thick with a 100 nm gap between them. They are completely surrounded by SiO2, except for a small, 500 nm strip of ITO material in the slot (Figure 1). A plasmonic mode is supported between the metal layers in the slot, with a high intensity and large modal overlap between the fundamental and second harmonic wavelengths. In this configuration, we generated a strong third harmonic signal, but almost no second harmonic signal. This third harmonic is the result of a cascaded $\chi^{(2)}$ process—second-harmonic generation followed by sum-frequency generation with the second harmonic mixing with the fundamental frequency. Because we only modeled the $\chi^{(2)}$ of ITO and not the third-order susceptibility, it has to be the result of a second-order process. However, it is unclear why the second harmonic signal did not show up in measurable quantities.

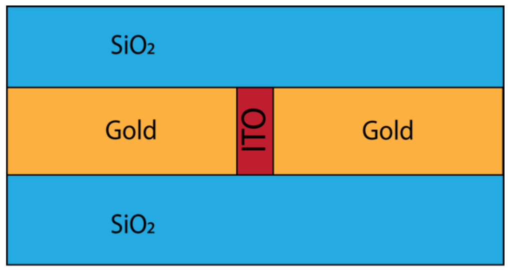

Figure 1. The cross-section of the slot waveguide simulations. The gap is 100 nm wide and the gold layer is 300 nm thick. Outside of the 500 nm long ITO region, the slot is filled with SiO_2.

RESULTS

Our simulations show SHG in free space with a custom material derived from the properties of ITO, an ENZ material. Additionally, by adding another light wave and adjusting the wavelengths we show three-wave-mixing in free space with a thin-film of indium tin oxide, verifying the expected nonlinear phenomena of sum-frequency generation (SFG), and difference-frequency generation (DFG) (Figure 2).

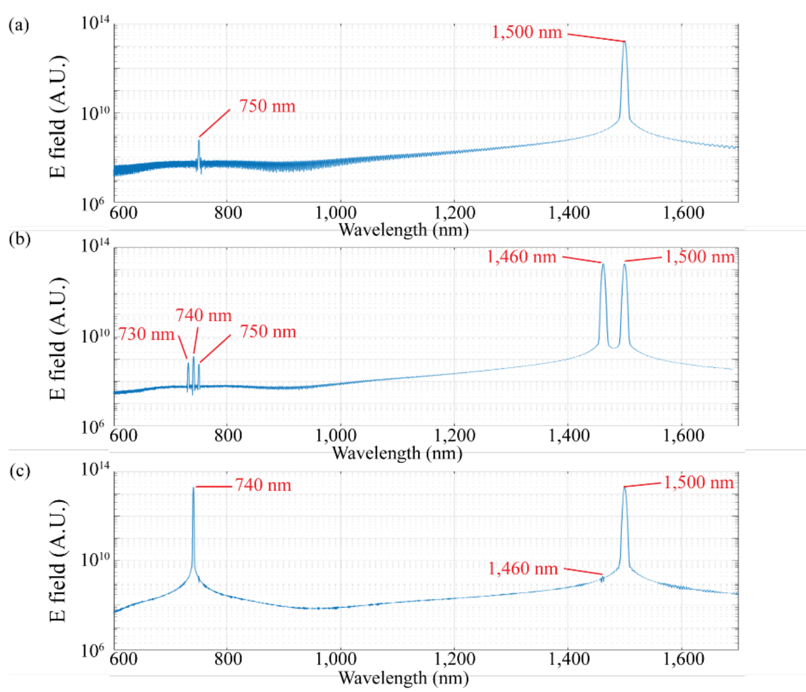

Figure 2. The spectra of our free space simulations with ITO in (a) SHG, (b) SFG, and (c) DFG. Approximate wavelengths of the spectral peaks of interest are marked on the graphs.

As previously mentioned, the plasmonic waveguide simulations for second-harmonic generation posed some unique challenges. Although phase-matching was not a concern (due to the near-zero index of the materials and the particular way Lumerical handles nonlinear optics), we ran into unique problems associated with ENZ materials. The first problem has to do with how the permittivity changes near the zero-permittivity wavelength. Typically, the permittivity decreases with increasing wavelength for these materials. That means that in a typical configuration, the permittivity will be basically zero or slightly negative for the fundamental (longer) wavelength, but will be positive for the second harmonic (shorter) wavelength. A negative permittivity corresponds to a metallic material and will support a plasmonic mode. However, the positive permittivity is dielectric, and will not support a plasmonic mode. This means that the modes supported at the fundamental and second harmonic wavelengths are different in nature, and will not have significant overlap, drastically reducing the efficiency of nonlinear conversion or preventing it altogether.

To alleviate this issue, we instead chose a plasmonic slot waveguide architecture. This allowed us to insert the ITO material in the slot, which is a configuration very similar to one that has been used in experiments by other researchers[15]. In this configuration, the modes between the fundamental wavelength and the second harmonic wavelength are nearly identical, leading to a high modal overlap which should translate to a large nonlinear conversion efficiency. One downside is that at the zero-permittivity wavelength, ITO will absorb more strongly than at other wavelengths, causing increased loss at the fundamental wavelength. In this configuration, instead of a second harmonic signal, we observed the third harmonic in a cascaded second-order process. The third harmonic also has high modal overlap with the fundamental and second harmonic in this configuration. We are investigating why the second harmonic signal is not generated in a measurable quantity in this configuration.

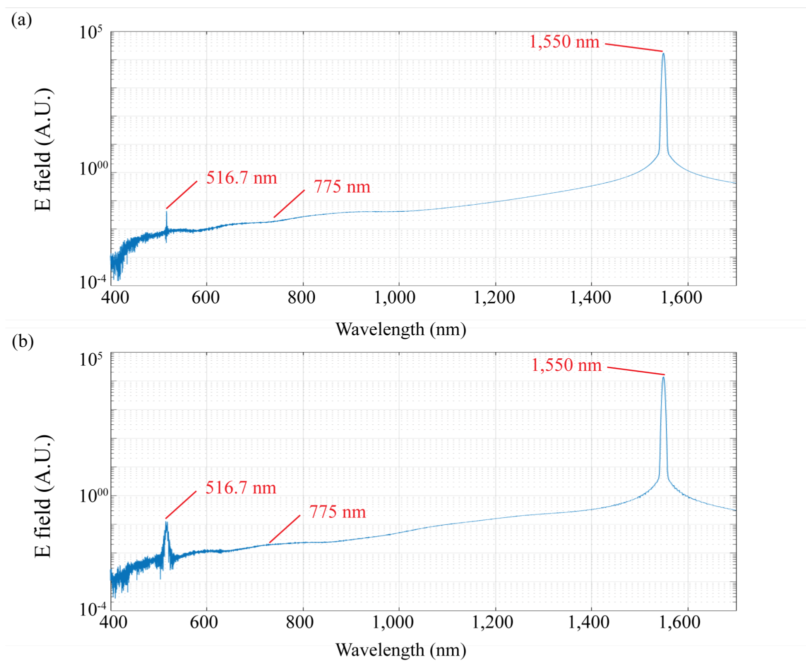

Figure 3. The spectra of our waveguide simulations, showing third-harmonic generation with a second-order nonlinear material a) where the ITO zero-permittivity wavelength is de-tuned from the fundamental frequency and b) where the ITO zero-permittivity wavelength is very close to the fundamental frequency. Having the zero-permittivity wavelength near the fundamental enhances the nonlinearity, but broadens the spectrum of the generated signal.

Figure 3 shows the spectra generated from the plasmonic slot waveguide in two different scenarios. In Figure 3a, the zero-permittivity wavelength is de-tuned from the fundamental wavelength (1,550 nm), whereas in Figure 3b, the zero-permittivity wavelength is very close to the fundamental. It is clear to see that having the zero-permittivity wavelength near the fundamental wavelength enhances the nonlinearity by generating a third harmonic peak with larger magnitude. However, the third harmonic peak is also broadened in the case where the ENZ wavelength is near 1,550 nm.

One possible explanation for not seeing the second-harmonic frequency is that the loss from the guided modes in this configuration is much higher than the loss associated with a free-space plane wave traveling through an ITO layer. Additionally, the second- and third-harmonic may experience much higher modal losses than the fundamental wavelength. In fact, we observed that if the ITO region was too long, the third harmonic would start to die out again (which may also be impacted by the phase-matching condition between the second and third harmonic). Furthermore, the third harmonic signal dies out quickly outside of the ITO region due to the high modal loss at this wavelength. Due to the higher loss, the second harmonic might die out quickly, with any generated signal mixing directly with the fundamental wavelength. We acknowledge that this geometry with a very short ITO region will be somewhat difficult to realize in practice. We are in the process of devising a way to fabricate these devices.

CONCLUSION

With second-harmonic generation, we could create a system to perform phase sensitive amplification, designing a proof-of-concept signal regeneration device with a smaller footprint than previous methods while still maintaining the increased bandwidth potential inherent to optical signals. This, in turn, would ultimately minimize device footprints of optical circuits, improving density and performance of all such circuits, since all circuits require signal regeneration. These smaller devices will be essential in the development of cascadable photonic logic devices, as they can act as a building block and alleviate the need for holistically designing regeneration into the entire circuit.

REFERENCES

[1] Touch, J., Cao, Y., Ziyadi, M., Almaiman, A., Mohajerin-Ariaei, A. and Willner, A. E., "Digital optical processing of optical communications: towards an Optical Turing Machine," Nanophotonics **6**(3) (2017).

[2] Umeki, T., Asobe, M., Takara, H., Miyamoto, Y. and Takenouchi, H., "Multi-span transmission using phase and amplitude regeneration in PPLN-based PSA," Opt. Express **21**(15), 18170 (2013).

[3] Puttnam, B. J., Mazroa, D., Shinada, S. and Wada, N., "Phase-squeezing properties of non-degenerate PSAs using PPLN waveguides," Opt. Express **19**(26), B131 (2011).

[4] Capretti, A., Wang, Y., Engheta, N. and Dal Negro, L., "Comparative Study of Second-Harmonic Generation from Epsilon-Near-Zero Indium Tin Oxide and Titanium Nitride Nanolayers Excited in the Near-Infrared Spectral Range," ACS Photonics **2**(11), 1584–1591 (2015).

[5] Capretti, A., Wang, Y., Engheta, N. and Negro, L. D., "Enhanced third-harmonic generation in Si-compatible epsilon-near-zero indium tin oxide nanolayers," Opt. Lett., OL **40**(7), 1500–1503 (2015).

[6] Wen, X., Li, G., Gu, C., Zhao, J., Wang, S., Jiang, C., Palomba, S., Martijn de Sterke, C. and Xiong, Q., "Doubly Enhanced Second Harmonic Generation through Structural and Epsilon-near-Zero Resonances in TiN Nanostructures," ACS Photonics **5**(6), 2087–2093 (2018).

[7] Argyropoulos, C., D'Aguanno, G. and Alù, A., "Giant second-harmonic generation efficiency and ideal phase matching with a double ε-near-zero cross-slit metamaterial," Phys. Rev. B **89**(23), 235401 (2014).

[8] Reshef, O., De Leon, I., Alam, M. Z. and Boyd, R. W., "Nonlinear optical effects in epsilon-near-zero media," Nat Rev Mater **4**(8), 535–551 (2019).

[9] Suchowski, H., O'Brien, K., Wong, Z. J., Salandrino, A., Yin, X. and Zhang, X., "Phase Mismatch–Free Nonlinear Propagation in Optical Zero-Index Materials," Science **342**(6163), 1223–1226 (2013).

[10] Wang, Y., Capretti, A. and Dal Negro, L., "Wide tuning of the optical and structural properties of alternative plasmonic materials," Opt. Mater. Express **5**(11), 2415 (2015).

[11] Johns, B., Puthoor, N. M., Gopalakrishnan, H., Mishra, A., Pant, R. and Mitra, J., "Epsilon-near-zero response in indium tin oxide thin films: Octave span tuning and IR plasmonics," Journal of Applied Physics **127**(4), 043102 (2020).

[12] Moerland, R. J. and Hoogenboom, J. P., "Subnanometer-accuracy optical distance ruler based on fluorescence quenching by transparent conductors," Optica **3**(2), 112 (2016).

[13] Vassant, S., Hugonin, J.-P., Marquier, F. and Greffet, J.-J., "Berreman mode and epsilon near zero mode," Opt. Express **20**(21), 23971 (2012).

[14] Newman, W. D., Cortes, C. L., Atkinson, J., Pramanik, S., DeCorby, R. G. and Jacob, Z., "Ferrell-Berreman modes in plasmonic epsilon-near-zero media," arXiv:1505.06180 [physics] (2015).

[15] Lee, H. W., Papadakis, G., Burgos, S. P., Chander, K., Kriesch, A., Pala, R., Peschel, U. and Atwater, H. A., "Nanoscale Conducting Oxide PlasMOStor," Nano Lett. **14**(11), 6463–6468 (2014).