Introduction:

Future advancements in integrated photonics technology require optical components that are both smaller and adaptable to function inside chip systems. Developing nonlinear optical processes on-chip remains difficult as they require strict phase-matching conditions, which are difficult to achieve using waveguides. Traditional phase-matching techniques, which use birefringent crystals or precise mode engineering, need long propagation lengths or cannot be adapted to the physical limitations of chip-based platforms.

Phase matching in nonlinear systems can be effectively achieved using Epsilon-near-zero (ENZ) materials. These materials have a real permittivity that approaches zero at specific wavelengths, leading to flattened wavefronts and spatially uniform field distributions. Indium tin oxide materials demonstrate epsilon-near-zero properties near telecom wavelengths (~1280 nm), enabling phase-free propagation and improving light-matter interaction in subwavelength structures.

The production of integrated waveguides at large scales presents difficulties because the typical fabrication techniques involved, such as e-beam lithography, tend to operate at slow speeds. 3D printing methods that address these challenges have recently been demonstrated by our collaborators at Whitworth University. Combining 3D printed structures with ENZ materials enables exploration into integrated nonlinear devices that eliminate conventional phase matching and enhance frequency conversion and signal modulation efficiency within reduced device sizes. Furthermore, the 3D printing fabrication technology is not only fast but also inexpensive. The combination of this technology with ITO would represent a very inexpensive and very scalable integrated nonlinear platform.

This study investigates how 3D printed ENZ waveguides address phase-matching constraints within nonlinear optical systems. We will use CW lasers in conjunction with spectrographs and an optical spectrum analyzer to measure any nonlinear output from the waveguides, such as second-harmonic generation or other three-wave mixing. Using these measurements in conjunction with beam profiler measurements, we aim to characterize the efficiency of these devices

Background:

The field of integrated photonics has been progressing rapidly to integrate complete optical systems into chip-scale devices. This technology has proven useful in applications as diverse as telecommunications and sensing, quantum information processing, and nonlinear signal manipulation. Photonic integrated circuits offer significant advantages because they support fast optical processing while consuming less power and occupying less space than traditional bulk optical systems. Researchers have found it difficult to downsize some optical systems due to fundamental nonlinear optics challenges, which create new complications.

Maintaining phase alignment between interacting light waves, known as phase-matching, determines the effectiveness or efficiency of nonlinear optical processes such as second- and third-harmonic generation and four-wave mixing. Phase matching remains crucial in nonlinear processes to maintain the in-phase relationship between the generated signal and the driving field throughout propagation. Without phase matching, the conversion efficiency is limited to the point of not being useful. Birefringent crystals and quasi-phase-matching techniques are common phase-matching approaches in bulk materials that modify the nonlinear susceptibility. Due to design limitations, restricted interaction lengths, and tightly confined optical modes, integrated waveguides encounter significant phase matching difficulties.

There has been recent interest in ENZ materials because they possess dielectric permittivity values that become close to zero at specific wavelengths. In this ENZ region close to the zero-epsilon wavelength, the material achieves an effective refractive index that approximates zero, allowing electromagnetic waves to propagate with negligible phase accumulation. This means light propagates through the medium while preserving a stable phase profile, simplifying nonlinear processes by reducing or eliminating the need for precise phase matching. ITO is an ENZ material that demonstrates specific behavior in telecom wavelengths while showing enhanced nonlinear optical characteristics.

Scaling the production of integrated waveguides for nonlinear optics presents substantial difficulties because traditional fabrication methods tend to be slow and expensive while offering limited design flexibility. Traditional lithographic techniques struggle to create complex three-dimensional structures that enable proper light-matter interaction and precise optical mode regulation. Existing lithographic processes like photolithography and electron beam lithography mainly produce flat structures, which restricts their ability to form the sophisticated geometries for advanced integrated photonic devices. Advances in additive manufacturing and 3D printing have enabled rapid prototyping of photonic components. These techniques also allow for the direct fabrication of complex volumetric structures on chip platforms, overcoming many traditional design limitations.. The demonstration of combining 3D printing technology with epsilon-near-zero materials will allow the development of new types of integrated nonlinear devices that overcome the limitations of traditional bulk nonlinear optics and typical on-chip nonlinear photonic approaches. These methods will simplify phase-matching requirements while increasing nonlinear efficiencies and shrinking the size, complexity, and cost of photonic circuits.

Methods:

We used commercially available indium tin oxide (ITO) thin films with thicknesses ranging from 120-160 nanometers deposited on standard microscope glass slides. These ITO-coated slides were purchased from Sigma-Aldrich and served as the ENZ-active layer. The slides were cleaned using isopropyl alcohol before use.

A custom-designed 3D printed waveguide was fabricated directly onto the ITO surface using a stereolithographic 3D printer with a resolution of approximately 10 μm. The waveguide design was developed in collaboration with Whitworth University and printed using a custom clear photopolymer resin. The design consisted of a ridge structure aligned parallel to the slide's length and spanned the central portion of the ITO film. The printed structure remained uncoated, and no cladding layer was added during testing. The output side of the waveguides were manually cleaved from the printed structures by utilizing a diamond scribe. The slide received shallow etches on top and bottom surfaces at intended points before pressure from the scribe's back caused the waveguide to crack along these etched lines. The standard application of this technique resulted in clean and straight facets, which worked well for optical coupling.

To couple light into the waveguide, we used a continuous wave (CW) fiber-coupled laser with a wavelength of 1310 nm. The laser was connected to a lensed fiber (OZ Optics), which is used to launch light into the waveguide (Figure 1). The beam entered from the left-hand side and was focused onto the waveguide edge using manual alignment with adjustable stages. The total interaction length between the input and output edges of the device was approximately 1.25 cm, limited by the width of the ITO slide.

On the right-hand side of the setup, an optical spectrum analyzer (OSA) from Thorlabs was used to measure transmitted and emitted light. The light output from the device was collected using a cleaved multi-mode fiber directed into the fiber port of the OSA. We use motorized piezo stages to align the fibers.

The near-field mode structure was monitored using a top-down visible-IR camera placed above the sample for capturing waveguide scattering and confinement. The beam profiler was set up off-axis to gather extra lateral details. The fiber-coupled spectrograph served as an output spectra monitoring tool, which provided lower resolution and sensitivity than the OSA but operated more easily and supported quick nonlinear signal generation checks during alignment.

No external phase-matching methods were employed in this experiment. Instead, we relied on the intrinsic properties of the ENZ regime within the ITO film to facilitate nonlinear interactions. Any observed harmonic peaks in the output spectrum were attributed to phase-free nonlinear propagation supported by the ENZ response.

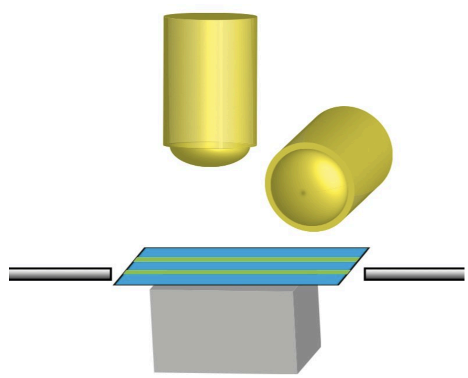

Fig. 1: Endfire Wave Guide Testing Setup

Expected Results/Problems:

Nonlinear optical signals, including second-harmonic generation and additional three-wave mixing processes, should be detectable from the 3D printed ENZ waveguides. When the ENZ regime of the ITO thin film effectively eliminates phase accumulation, nonlinear conversion becomes possible without traditional phase-matching requirements. The OSA or spectrograph should detect harmonic peaks in the output spectrum as a result. The top-down camera and lateral beam profiler should demonstrate localized field confinement inside the waveguide region, especially close to the ITO's zero-epsilon wavelength.

Observed nonlinear signals might exhibit reduced clarity and strength due to multiple contributing factors. When a diamond scribe manually cleaves the waveguide, the resulting angled or uneven facets decrease coupling efficiency at the output points. Imperfections in the printed structure, together with defects and surface irregularities, can cause more scattering, which reduces mode confinement. The spectrograph's lower resolution and sensitivity compared to the optical spectrum analyzer make it hard to identify weaker harmonic signals. Continuous-wave lasers with limited optical power power the experimental setup which lacks standard polarization control needed for phase matching thus producing weaker nonlinear signals compared to systems utilizing pulsed lasers. The ability to detect any nonlinear peaks supports the hypothesis that phase matching becomes relaxed within ENZ-based waveguides, even with the present limitations.

Conclusion:

The research explores how 3D printed epsilon-near-zero (ENZ) waveguides provide solutions to phase-matching problems in integrated nonlinear optical systems. Our research focuses on showing that nonlinear optical signal generation can be achieved by integrating indium tin oxide (ITO) thin films with tailored 3D printed structures which eliminates the need for conventional phase-matching methods. ITO's ENZ characteristics at telecommunications frequencies result in low phase accumulation for light propagation thus easing phase-matching requirements which helps achieve nonlinear effects in small chip-based devices.

The system uses continuous wave lasers alongside spectrographs and beam profilers to measure harmonic signals and examine waveguide field confinement. The identification of nonlinear peaks shows that ENZ waveguides can minimize phase matching requirements despite possible signal strength reductions due to cleaving imperfections, low laser power, and structural defects. Working with ENZ materials alongside 3D printing enables an economical and scalable method to create compact nonlinear photonic devices. Advancements in printing resolution, together with better alignment and input coupling methods, will continue to boost the platform's efficiency and reliability.