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Author

Azcoitia, Gia

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Carrier Envelope Phase Stabilization via Integrated Brillouin Scattering in Chalcogenide Rib Waveguides

Gia Azcoitia[1]

[1] *Department of Electrical and Computer Engineering, University of California, Los Angeles, Los Angeles, CA, 90095, USA*
**gia624@ucla.edu*

Abstract: This work proposes a novel method of CEP stabilization via frequency shifting through the leveraging of stimulated Brillouin scattering in a chalcogenide rib waveguide enabling integrated and compact pulse control at 1550nm.

INTRODUCTION

Carrier-envelope phase (CEP) stabilization is a critical component in the pursuit of few-cycle, high-precision optical pulses for applications within attosecond science. The 2019 work by Lemons et al. demonstrates a feed-forward technique using an acousto-optic frequency shifter (AOFS) to pre-compensate for CEP drift in an Er:Yb:glass mode-locked laser [1]. AOFS devices, however, require high RF power, and increase total loss of a system due to insertion loss. Along with this, AOFS devices are bulk optics making them difficult to implement on smaller scale systems.

As such, an alternative method for achieving frequency shift can be found through the leveraging of nonlinear effects, namely simulated Brillouin scattering (SBS) within a waveguide. With this approach, single digit attosecond stabilization at telecom wavelengths may be achieved without the aforementioned limiting factors. This, therefore, opens a new direction in applications requiring ultrastable frequency and time precision such as high resolution spectroscopy and fiber timing networks [1]. The particular relevance from this SBS approach is its compatibility with on chip integration, therefore producing a stable and compact system.

METHODS

In this investigation, SBS will be evaluated as a means of achieving CEP stabilization. SBS occurs when an intense pump wave induces acoustic phonons in a medium, leading to scattered Stokes waves shifted by the Brillouin frequency governed by the following: $f_B = \frac{2nv_a}{\lambda}$ where n is the refractive index of the material, v_a is the velocity of an acoustic wave in said material, and λ is wavelength [2]. Unlike AOFS systems which rely on acoustic gratings, Brillouin systems utilize intrinsic material nonlinearities and can be fully integrated into photonic circuits. Furthermore, recent advances in chalcogenide rib waveguides have enabled on-chip SBS generation with compact footprints [3].

As such, this design must be carefully crafted in order to seamlessly mimic the effect of the AOFS exactly as in the aforementioned experiment. That is, we must achieve a frequency shift of 80MHz [1]. In order to attain this, a MATLAB study was conducted on the required acoustic velocity to produce said shift. Keeping in mind, the index of refraction of a chalcogenide rib waveguide composed of As_2S_3 is approximately 2.4 [3], we see that the acoustic velocity must be approximately 25 m/s. Therefore, this acoustic velocity must be achieved via a slow wave engineering approach.

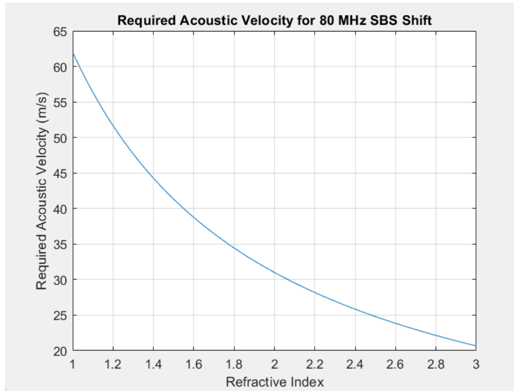

Fig. 1. Required Acoustic Velocity at f_B=80MHz for n =2.4 (Ref [2])

We present the expression: $v_a = \sqrt{\frac{E_{eff}}{\rho_{eff}}}$, where E_{eff} is the effective Young's modulus and ρ_{eff} is the effective density of the engineered structure [4]. That is, a reduction in stiffness can possibly prove sufficient enough to reduce acoustic velocity, particularly, via the reduction of material and mechanical parameters. For example, cladding the waveguide in a soft material such as Benzocyclobutene (BCB) can prove useful in lowering the stiffness of the system [5]. Along with this, the introduction of perforations onto the waveguide, akin to [6], will also further reduce stiffness.

RESULTS AND INTERPRETATION

The primary result of this investigation is the identification of a chalcogenide rib waveguide structure capable of supporting a tailored acoustic mode velocity of approximately 25 m/s, a requirement dictated by the Brillouin frequency shift condition for an 80 MHz frequency offset at 1550 nm. This shift replicates the effect achieved using an AOFS in the Lemons et al. experiment but does so via fully integrated photonic structures without the need for bulk acousto-optic components.

By applying slow-wave engineering principles, specifically, by lowering the effective stiffness and increasing the effective density through structural geometry and potential layering with compliant materials, literature suggests that it is theoretically possible to reduce the acoustic velocity of the rib waveguide to the required regime.

A conceptual SBS-based frequency shifter is then proposed: a specially designed chalcogenide rib waveguide with integrated pump/signal ports, coupled into a feedback loop where the frequency-shifted Stokes signal is routed into the mode-locked laser cavity. This mimics the feed-forward configuration used in Lemons et al., but eliminates the need for bulk optics, RF driving electronics, and associated insertion losses [1].

CONCLUSIONS

This paper examines the potential of replacing AOFS with Brillouin-based optical frequency shifters in CEP-stabilized mode-locked laser systems. Though AOFS remains the current standard due to its simplicity and proven efficacy, SBS techniques provide a compelling alternative for compact, photonic-integrated implementations, particularly in scenarios where device miniaturization is desired. Future work will include experimental validation of SBS-based CEP stabilization and comparison of its timing jitter using the Haus-Mecozzi formalism [7].

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