Spectral Hole Burning based LIDAR

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Abstract

We present a novel technique for LIght Detection And Ranging (LIDAR), which uses the recording and readout of high-bandwidth, spatial-spectral holographic (SSH) gratings. We transmit a random noise laser signal spanning greater than 10 GHz, and record the return signals as spectral gratings in an SSH by interfering them with the transmitted signal. Finally, reading out the resulting SSH grating with a chirped laser, detecting and performing an FFT completes the required LIDAR post-processing.

1 Introduction

In the past, spatial spectral holographic (SSH) techniques have been used in photonic signal processing applications such as high bandwidth signal correlation[1] and arbitrary waveform generation[2]. More recently, these techniques have been applied as building blocks in high bandwidth RF array imagers[3], multi-channel RF spectrum analyzers[4, 5] and radar ranging systems[6]. While the bandwidth of these SSH materials can be as high as 200 GHz in inorganic crystals, and up to several THz in organic compounds, to date only a handful of experiments have operated over more than a few GHz.

A recent shift in experimental technique[6] has allowed researchers to use SSH materials with high bandwidth inputs, and read the resulting spatial-spectral features out at a much lower data-rate. This process is of particular interest to radar and LIDAR, where one typically does not care about the high bandwidth transmit signals themselves, but rather just the range, velocity and reflectivity of each target. This is an application that is well suited to SSH signal processing, since the high bandwidth reference waveform and the time-delayed return waveform write a spectral grating whose period is $\Delta\nu = \frac{c}{2R}$. Wideband readout is enabled by sweeping the frequency of a laser while a calibration spectral measurement allows the chirp non-linearities to be calibrated out as if the laser chirp was perfectly linear. This avoids the need for wideband RF chirp sources with their corresponding limits and eliminates the double sideband nature of EO modulation.

In this paper, we show how we can generate and use a random-noise laser signal in conjunction with SSH techniques for a LIDAR application, and how to apply the recent advances in high-bandwidth readout to the problem of high bandwidth random-noise LIDAR.

2 SSH basics

Spatial-spectral holography is the process by which spectrally varying spatial absorbtion gratings are formed in materials that consist of inhomogeneously broadened absorbers (IBA). As is shown in Fig. 1, the narrow homogeneous lines of rare-earth ions doped into the crystal lattice are shifted throughout a wide inhomogeneous band by the variation of the ions' local environments, for instance due to the specific configuration of other nearby dopant ions and the perturbations they exert on the crystal lattice. In the material we use for our experiment (0.5% doped Tm^{3+}:YAG cooled to 4.8 K), the inhomogeneously broadened linewidth spans $\Gamma_I = 25$ GHz, while the homogeneous absorbtion width is $\Gamma_H = 10 - 100$ kHz.[7] Since this highly doped crystal has $\sim 10^6$ dopant ions per smallest optically addressable volume ($\lambda^3 \approx 1\mu\text{m}^3$), one can assume that typical interaction regions ($> 10^6\mu\text{m}^3$) consist of a well-sampled inhomogeneously broadened line. Since Tm^{3+}:YAG is a two-level system with an intermediate bottleneck state (where the decay-rate from the excited state into the bottleneck state is fast), any spectral features written into Tm^{3+}:YAG will persist for the bottleneck state life time $T_B = 10$ ms, during which they can be read out.

Early RF signal processing demonstrations using SSH media proved the feasibility of using these materials in systems ranging from high bandwidth signal correlation[1] to arbitrary waveform generation.[2] Most of the initial applications made use of the high bandwidth correlative properties that these materi-

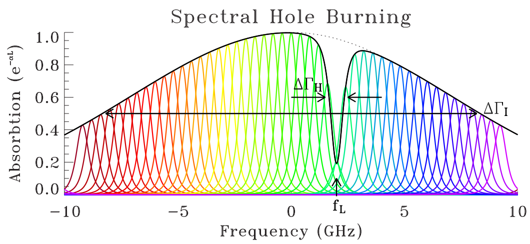

Figure 1: Inhomogeneously broadened absorber - Individual Lorentzian lines are inhomogeneously shifted due to the local crystal field.

als possess.[8] However, since these systems require high bandwidth inputs and outputs, they can be I/O limited if not designed carefully. The more recent S2CHIP approach circumvents the high bandwidth output problem by recording high bandwidth spectral features in the SSHs, then reading them out slowly with a chirped optical source, and finally performing some form of low-bandwidth post processing.[6] The appeal of this approach lies in its capability of converting high bandwidth data into an easier to detect and digitize low bandwidth signal.

One particular function that these materials can perform is time-delay measurement as required in radar and LIDAR. For this, consider a pair of high bandwidth time-delayed pulses (or in fact any pair of high bandwidth waveforms) which illuminate the IBA. After the first pulse strikes the IBA, the differential phase advance of the excited and ground state is deterministic for all resonance frequencies in the inhomogeneous band for the duration of the coherence lifetime. If a time-delayed copy of the same optical pulse strikes the IBA within the coherence time of the excited state ($\approx 10\mu s$ in Tm^{3+}:YAG), the linearly varying differential phase delay of the two pulses for the different spectral bins will result in a sinusoidal absorbtion spectrum that will persist in the crystal for the duration of the bottleneck state lifetime, T_B. This absorbtion grating will have a period that is inversely proportional to the range delay ($\Delta\nu = \frac{c}{2R}$). Such a sinusoidal spectral grating can then be read out with a chirped source, and the range of the target, R, can be infered. This mechanism gives access to an all-optical LIDAR range detection mechanism, which is the focus of the rest of this document.

3 SSH based LIDAR

LIDAR makes use of optical signals to perform range, velocity, rotation and/or chemical composition measurements of distant objects. The simplest measurement is typically done by emitting an optical pulse, and measuring the return delay as a range resolved return profile. Just as in radar, modulated pulses can also be used by correlating the return against the transmitted reference. In coherent systems, the return may be interfered with a time-delayed copy of the transmit signal to perform Doppler processing, in order to measure the relative motion of the object with respect to the LIDAR source. In this paper we will discuss LIDAR ranging using SSH, although extensions to Doppler processing are also possible. The feature that makes IBA materials interesting for the LIDAR application is the excited state coherence time of on the order of 10 - 100 μs. As explained above, this coherence allows the material to 'remember' the phase of previous optical interactions for 10 - 100 μs. Therefore, any LIDAR returns that hit the IBA within a few coherence times create spectral gratings with the information of the target range encoded as the fringe period in the spectral domain.

Figure 2 shows the proposed experimental setup. We will use a broad band laser source as the LIDAR transmit signal source. We split this source up with a PBS, with the undelayed path going directly into the IBA, and acting as a zero-delay reference. The bulk of the noisy lasers output, however, goes through a true-time delay to simulate the LIDAR time-of-flight delay. Instead of using a single-pass fiber delay line, we are opting for a double-pass geometry, in which a Faraday rotator at the end of the fiber switches the light emitted from the fiber to its orthogonal polarization before relaunching it back through the fiber (see Fig. 2). The counterpropagation through the fiber will undo all the polarization scrambling that was induced on the first trip through the fiber. The delayed light will then be focused into the same volume of the crystal that already has had the original transmit signal pass through it. The linear differential phase ramp of the excited state ions with respect to this second optical signal will cause a sinusoidal spectral absorbtion grating to be formed. The periodicity of this grating contains all of the information required to recover the range delay.

4 High Bandwidth Readout Linearization

Reading out high-bandwidth spectral gratings for signal processing in SSH materials (such as those created by the presented LIDAR processor) is a non-trivial problem. While the materials promise enormous signal processing bandwidths approaching 10's or even 100's of GHz, the problem lies in the creation of an

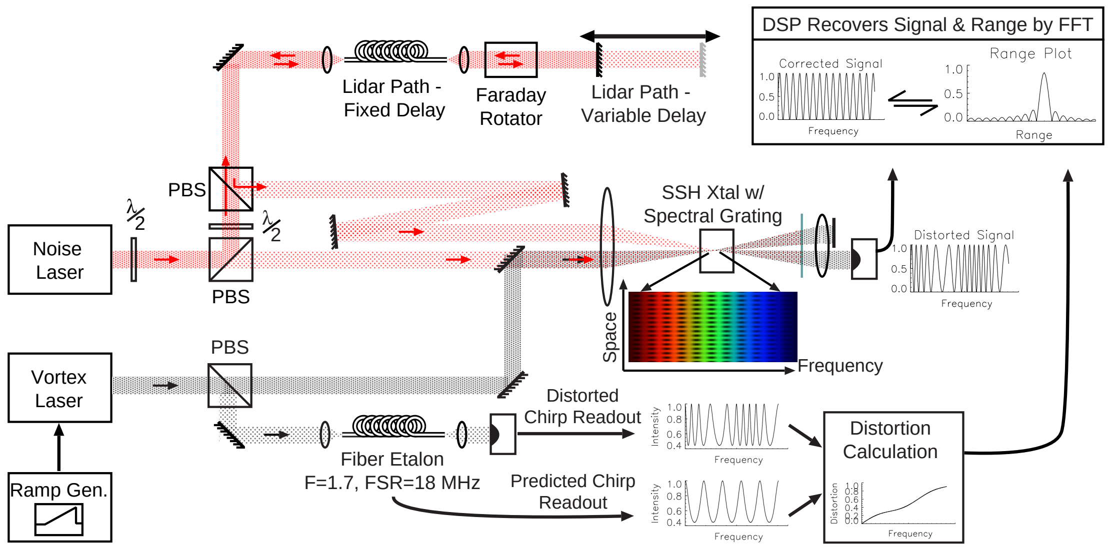

Figure 2: LIDAR demonstrator with high bandwidth spectral grating readout linearization post-processing. A noisy laser creates high bandwidth optical signals which split, with a small fraction acting as a non-delayed reference signal for the IBA material. A large fraction of the high BW signal is launched into a fiber, which simulates a range delay of up to 1.5 km. The optical return is injected into the IBA, and writes a spatial-spectral grating with a fixed spatial frequency, and a spectral grating period which is determined by the temporal seperation of the reference and LIDAR return signals. A seperate swept laser reads the grating, while also creating a reference signal through a fiber etalon interaction. The etalon signal acts as frequency ruler, and can be used to correct the IBA spectrum readout which ultimately gives the correct range information of the LIDAR system.

optical, high fidelity, high bandwidth signal that has the appropriate format for readout (for example, a $T_1 = 10$ ms duration chirp, spanning the full bandwidth). Approaches to creating lower bandwidth (0.1 - 3 GHz) optical chirps for SSH readout include the use of RF sweepers, arbitrary waveform generators, and pulse pattern generators (PPGs), which modulate an optical carrier with an upper and lower sideband with the use of an EOM. These approaches are usually limited by the RF generators for different reasons. RF sweepers usually stich together multiple sub-octave-spanning bandwidths, and arbitrary waveform generators have clock rates that are too slow to create 10 GHz chirps. Of the RF techniques mentioned, PPGs have been applied with the greatest success[6] despite their binary nature, which creates higher order harmonics that can limit their use.

A second technique for chirp-generation is to create a chirping laser that can cover several tens or hundreds of GHz, and use it to read out the SSH. Unfortunately, most chirping laser systems inherently chirp non-linearly over the bandwidths of interest, and so one either has to build open-loop chirping systems and suffer the resolution penalty, or create a feedback system to actively control the frequency as the chirp occurs (as in Agilent's 81900 laser series, which still has a 20 MHz frequency error specification). Our approach is different from the first two, since we correct the temporal distortion of the signal of interest after detection. Several lasers which are interesting for the open-loop chirping application are an intracavity EOM based system which has successfully chirped over 50 GHz[9], and the family of frequency shifted feedback lasers, as well as a host of Nd:YVO_4[10] and Nd:YAG[11] based systems, which unfortunately lase at 1064 nm or 1319 nm, and are not resonant with any demostrated rare-earth IBA transition.

We intend to read out spectral features in the SSH crystal by creating an optical chirp by using a commercial Littman ECDL, and digitizing the read-out spectral signal of interest (SOI) with all its temporal aberations (due to non-linearities in the chirp) in a digital oscilloscope. At the same time that the SOI is read, we will couple a small portion of the optical readout chirp into a long cavity with a correspondingly low free spectral range (FSR $= \nu_F = \frac{c}{2nL}$, where n is the index inside the cavity, and L is its length) and thus create a calibration signal. Since the shape of the calibration signal is predetermined to have the form

$$I(\nu) \quad = \quad \frac{I_{max}}{1 + (2\mathcal{F}/\pi)^2 \sin^2(\pi\nu/\nu_F)},$$

(where I_{max} is the maximum optical intensity, $\mathcal{F}$ is the cavity's Finesse, and ν represents the frequency being injected into the cavity), we can now precisely determine the amount of distortion present in both the 'calibration' signal and the SOI. Since we want to build a 'ruler' that can be used to an accuracy of MHz, we plan to use a FSR of 10 - 20 MHz, which will require a cavity length of approximately 5 - 10 meters, and perform curve-fitting on the resulting outputs. A very convenient way to build such a cavity is in fiber, since the end-faces of a fiber provide a 4% reflection (resulting in a Finesse of $\mathcal{F} = 1.7$). This readout mechanism is illustrated graphically in Fig. 2, which shows the readout in a LIDAR system. The lower half of Fig. 2 shows the swept readout laser and the calibrations signal generator. We have performed a set of experiments to prove that this readout mechanism with post-processing is in fact applicable to reading out SSHs with Littman ECDLs, and have found that the standard deviation of the spectral error went from 20 MHz to less than 1 MHz over the entire 9 GHz readout that was performed.[12] The attractive features of this readout are its simplicity and low cost, while potentially being able to create chirps in excess of 100GHz with off-the-shelf components.

On the whole, this SSH LIDAR system circumvents three important technological hurdles. First, the broadband transmit source does not have to be deterministic in nature, because we are taking advantage of the coherence time of the excited state of the SSH. Introducing the SSH, however, introduces the problem of having to read out a large spectral bandwidth in a relatively short amount of time, but we have shown a solution to this problem by applying the post-detection calibration, as explained above. Finally, even though this LIDAR system could use optical bandwidths approaching 100's of GHz, this implementation does not require high bandwidth intensity detectors, since the multi-GHz spectral information in the absorbtion band is turned into a MHz rate amplitude modulation in the readout process. This high- to low-bandwidth conversion is the primary feature of this LIDAR technique.

5 Conclusion

We have shown the concept of a LIDAR processor that records range-information of the target in the absorbtion spectrum of an inhomogeneously broadened absorber in the form of a spatial spectral hologram. Since SSHs have the capability of recording signals with 10's - 100's of GHz of bandwidth at sub MHz resolutions, they are ideal candidates for this application, since the high bandwidth LIDAR data can later be read out at a much slower rate using a chirped laser. This LIDAR system acts as a bandwidth converter that eliminates the complexity of the high bandwidth, time-delayed signals, and turns them into a much more elegant, low bandwidth readout signal that has the information of interest easily accessible.

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