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Ultrasound Detection Using Dispersion Due to Spectral Holes

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Abstract: Detection of ultrasound requires high efficiency phase to amplitude conversion. We demonstrate detection using dispersive effects in hole-burning materials which have large étendue compared to conventional methods. We show high sensitivity using modest hole parameters.

OCIS codes: (170.7170) Ultrasound; (070.1060) Acousto-optical signal processing

1. Introduction

Ultrasound is often used in non-destructive imaging. Most applications using this modality require a transducer in intimate contact with the sample. However, removing this restriction would allow a wider variety of applications. Techniques to use air-coupled ultrasound are being actively pursued [1], however sensitivity is limited by small coupling between vibrations in the test object and air due to a large impedance mismatch.

Optical detection appears to be a viable solution to the problem. The basis of this follows from the fact that light becomes phase modulated as it interacts with an object vibrating at ultrasonic frequencies. The problem then is to demodulate the phase modulation into an amplitude modulation which can be detected using photodetectors. Several approaches have been previously demonstrated using interferometric methods [2, 3] or adaptive imaging techniques including photorefractive crystals [4] and holography[5]. While these techniques perform well in situations where the received light is in a well-defined mode, in real world situations the received light is generally highly spatially multimode.

The ability for an optical system to gather light is characterized by its étendue, defined as $\mathcal{E} = \Omega A$ where Ω is the collection solid angle and A is the detection surface area. Due to the constant brightness theorem, adding optics to the system to increase the collection angle or surface area does not improve the étendue. Interferometry suffers from poor sensitivity in real world settings as its étendue is limited to $\sim\lambda^2$ due to the antenna theorem[6]. Confocal Fabry-Perot interferometers can achieve better with étendue of about 10^{-3} sr mm^{-2}[7].

Ultrasound detection using cryogenically cooled rare-earth samples has recently been demonstrated [8]. In that work, a spectral hole was prepared in a sample of Tm:YAG at the ultrasound frequency. This allows that particular sideband to be detected directly, by absorbing the unmodulated (carrier) beam. Used in this manner, the rare-earth doped sample allowed an étendue several orders of magnitude higher than has been achieved using other techniques. In real world applications however, the modulation signal is weak. Hence to obtain high sensitivity using this method requires large absorption away from the hole, while simultaneously obtaining high transmission through a narrow hole, which can be difficult to achieve.

We present an alternative method of ultrasound detection using the dispersive effects of spectral holes. Due to a steep change in absorption, light passing through the hole obtains a phase shift as dictated by the Kramers-Krönig relations. We apply this phase shift on the carrier portion of the light to obtain a beat signal with the sidebands, which can be detected. In an ideal case, a $\pi/2$ shift would completely convert the phase modulation to amplitude modulation. Furthermore using the carrier as a local oscillator allows shot noise limited detection of this amplitude modulation.

2. Experimental results

We report on experimental demonstration with the setup shown in Figure 1. The sample used is 0.1% Tm:YAG and is cryogenically cooled to 2.7 K. We used a diode laser opto-electronically locked to the same sample to provide a frequency reference. The engraved spectral hole has a linewidth of 371 kHz and an optical depth of 0.5, as shown in Figure 2. From these hole parameters, we expect a maximum phase shift of 0.14 rad. Initial calibration of the system was done using an EOM to modulate the beam.

As a proof of principle, we used a PZT mounted mirror to produce ultrasonic vibration at 1.11 MHz. To obtain a large phase shift, we shifted the laser frequency 39 kHz to the side of the hole as shown by the arrows in Figure 2. The demodulated signal was high pass filtered and amplified before being mixed down to obtain the retrieved signal as shown in Figure 3.

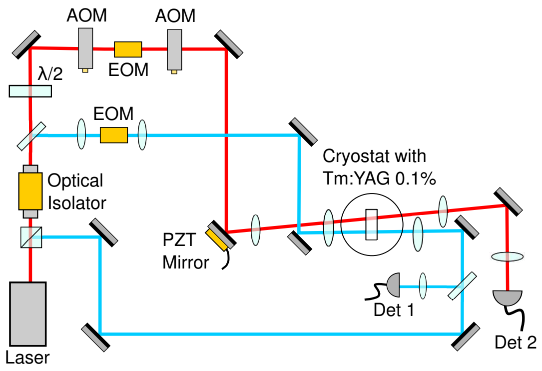

Fig. 1. The experimental setup. The experimental beam (in red) is frequency shifted and gated using two AOMs. The ultrasonic pulses were applied using a PZT-backed mirror. The beam is then steered through a prepared Tm:YAG 0.1%. The laser is locked to a spectral hole using a method similar to Bottger *et al.* [9] (path in blue), except with optical feedback.

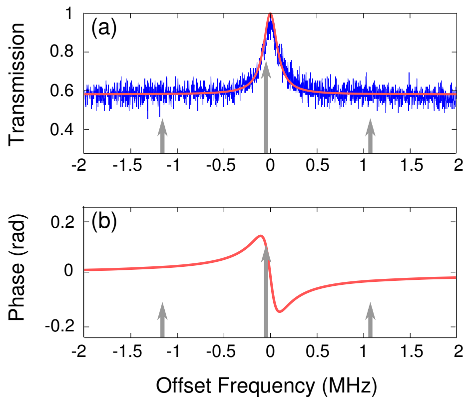

Fig. 2. The hole response. (a) shows the transmission of the spectral hole used, and (b) its corresponding phase shift. The arrows indicate the position of the carrier and sideband frequencies respectively.

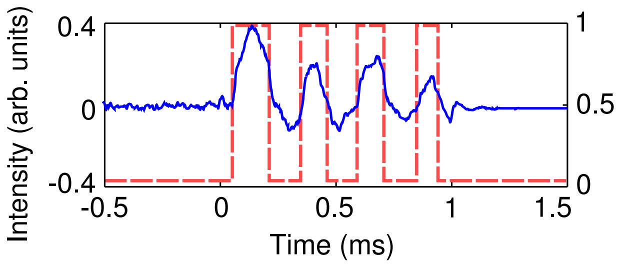

Fig. 3. Pulsed ultrasound detection. The green dotted line indicate the input pulse sequence, while the blue solid line shows the retrieved signal.

The position equivalent noise in the ideal case can be calculated by assuming shot noise detection and $\pi/2$ phase shift. Using this, we obtain a noise of 1.3×10^{-13} m/$\sqrt{\text{Hz}}$. However from our measurements, we obtain a position equivalent noise a hundred times larger of 4.6×10^{-11} m/$\sqrt{\text{Hz}}$ for a 30 kHz detection bandwidth. The reason for increased noise on our detection is two-fold: the sample used has a non-optimum optical depth leading to reduced phase-to-amplitude conversion, and there is residual phase noise on the laser at ultrasonic frequencies. However this does not affect the validity of our results.

3. Conclusion

We have demonstrated sensitive coherent optical detection of ultrasound using the dispersive effects of spectral hole burning media. This technique allows much larger étendue by using rare-earth ion doped samples. We have also shown that high sensitivity can be obtained from our method using relatively modest spectral hole properties.

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