Rubidium vapour based adaptive interferometer for laser ultrasound detection

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Rubidium vapour based adaptive interferometer for laser ultrasound detection

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Abstract. We describe an application of dynamic holography in rubidium vapour for laser ultrasound detection. This medium combines good signal to noise ratio with high cut-off frequency of approximately 1MHz.

1. Introduction

The generic scheme of adaptive interferometry is presented in figure 1. The dynamic holographic medium with a response time τ produces a thick phase hologram, which can be regarded as a beamsplitter reflecting part of the beam 1 in the direction of the beam 2 and vice versa. In a steady state there is no intensity transfer between writing beams, but instantaneous phase shift in a signal beam results in a transient energy transfer between the signal and the pump. The magnitude of this transfer is proportional to the phase shift. The duration of the transition process is determined by the hologram writing /erasing time τ. The adaptive interferometer automatically maintains an optimal quadrature condition and can compensate for speckles and slow environment - induced phase shifts. The use of photorefractive crystals in adaptive interferometers is described in [1]. The conceptually similar device based on holographic currents in photorefractive crystals (non-steady state photo-EMF effect) was also studied extensively [2].

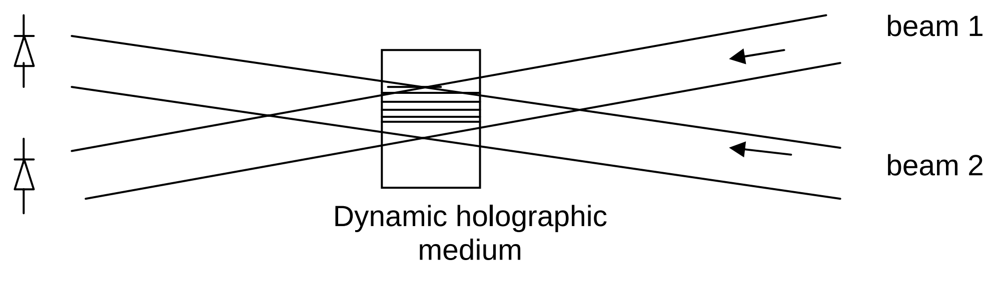

Figure 1. The principle of adaptive interferometry. Two beams write a hologram in a medium and diffract on it. The photodetector pair detects rapid phase shifts, which are not compensated by a medium.

The adaptive interferometer ability to compensate for environment-induced phase drifts and beam distortions is in direct proportion to the material cut-off frequency $\nu = (2\pi\tau)^{-1}$. For semiconductor photorefractives, such as GaAs, and laser power in 100 mW range, this frequency is 0.1-1 kHz , which can make difficult device operation in noisy conditions . For the non-steady-state photo EMF detector, the cut-off frequency of a few MHz is possible, but the signal to noise ratio is typically worse than for holographic devices [2], which limits its performance in laser ultrasound detection. For laser ultrasound applications, where spikes typically have submicrosecond duration, the optimal cut-off frequency has to be in the MHz range.

Rubidium vapor has a number of attractive properties as a dynamic holographic medium. For power range of tunable semiconductor lasers, its diffractive efficiency is high (>10%) , and the response time is 20-200 ns [3], which results in a sensitivity (defined as the energy per cm^2 necessary to write a 1% efficient hologram) approximately four orders of magnitude better, than that one of the most sensitive photorefractives. The rubidium cells are cheap, they have excellent optical quality, and holographic properties of all of them are identical. The vapor concentration is easily controlled by temperature. The difficulties of work with rubidium include the necessity of fine laser frequency tuning, the geomagnetic field protection, and the polarization control. Additionally, optimal conditions for hologram writing can involve nontrivial combinations of writing beam polarizations, laser frequency and external magnetic field. The nonlinear properties of rubidium, though quite complicated, can be derived using a density matrix formalism with a computationally intensive numerical procedure [4].

2. Experimental results

The setup we used to demonstrate ultrasound detection with rubidium based adaptive interferometer is shown in figure 2 (see also [5]). The beam of 780 nm <50 mW produced by a tunable semiconductor laser with an external cavity is split. The signal beam is reflected by the ultrasound-driven mirror, and crosses a pump beam at a small angle within a 75 mm long natural rubidium cell. The polarization of the reference beam is rotated 90 degrees with a half wave plate. The rubidium cell is protected from the geomagnetic field by a mu-metal chamber with incorporated electric heater.

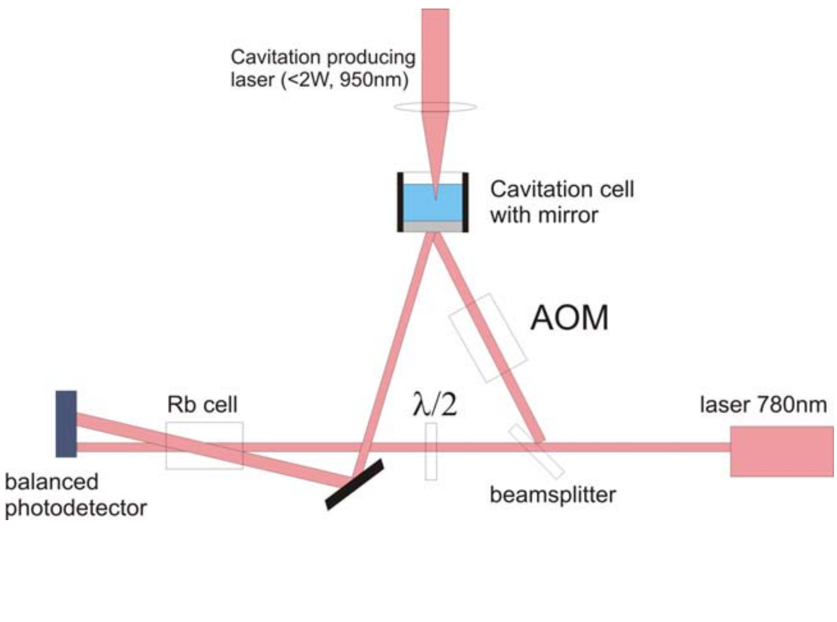

Figure 2. Optical setup for the detection of cavitation-induced ultrasound.

The optimal operation conditions for beams of nearly equal intensities are obtained for the magnetic field close to zero. The electro-optical modulator giving the sinusoidal phase modulation of 150 mrad at 8 MHz is included for calibration purposes. For operation, the cell is heated to 80-100 ºC.

The best results for our laser power are obtained in ^{87}Rb D2 Fg=2 transition. For better signal to noise ratio, the signal and pump must have mutually orthogonal nearly linear polarizations. This is related to the complicated transition structure, and this feature is confirmed by the numerical analysis, similar to reported in [4]. The atomic coherent states are sensitive to the polarization ellipticity, thus the optical properties of the illuminated atoms depend on the local polarization state, which changes, and not on the total local intensity, which is constant. This permits to write a hologram with a complicated polarization properties.

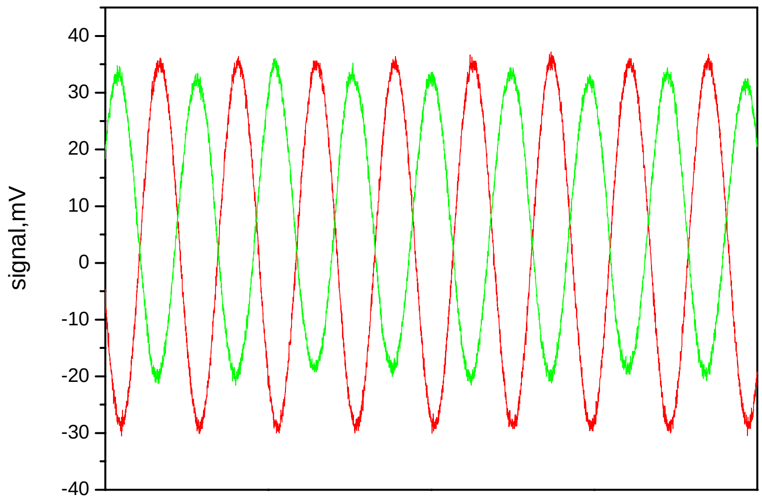

Figure 3. The photodetector pair response to 8.3 MHz phase modulation with 150mrad modulation amplitude.

In figure 3 we present the photodetector pair response to the sinusoidal phase modulation introduced in one arm of the interferometer with an electro-optic modulator. It is seen, that the signals have nearly equal amplitudes and 180 degrees phase difference. The balanced photodetector is used to suppress the laser intensity noise. The noise equivalent phase modulation in 20 MHz frequency band is 1-2 mrad, which corresponds to ~0.1 nm noise equivalent surface displacement. Since the cut-off frequency in rubidium is ~1.0 MHz, even the additional 1000 rad phase modulation at 200 Hz introduced with a loudspeaker driven mirror does not diminish the signal more than 1% [5].

The optical detection of the ultrasound induced in the aluminum plate by the Nd:YAG laser pulse, and by the piezoelectric transducer was reported in [5]. Here we demonstrate the adaptive detection of ultrasound generated by a CW-laser induced cavitation. The 5 mm thick cell is filled with a liquid strongly absorbing in infrared (water solution of cupric nitrate). The front window is made with 1.7 mm thick glass, the back window is 2.7 mm thick and coated with aluminum. By loosely focusing 0.1-2 W laser beam inside a liquid, the single cavitation bubbles are created. On collapse, the strong ultrasound shock wave is generated. The details are reported elsewhere [6]. The obtained signals have good SNR, and the surface displacement is comparable to that one produced by a Nd:YAG laser pulse.

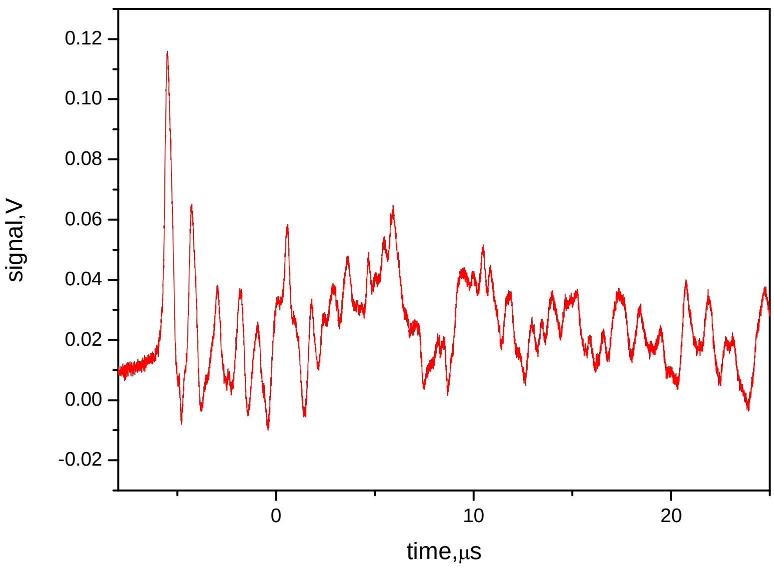

Figure 4. The differential photodetector signal produced by the mirror displacement resulting from the cavitation shock wave in a cell. Multiple wave reflections on boundaries are observed.

3. Conclusions

In conclusion, the use of rubidium as a dynamic holographic medium permits to detect the laser - induced ultrasound with a good signal-to noise ratio, comparable to that of the photorefractve crystals based adaptive interferometers. Rubidium demonstrates excellent adaptive properties because the hologram writing time in it is less than 1 microsecond, which is 3-4 orders of magnitude smaller, than for the fastest photorefractive crystals.

References

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