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NONLINEAR OPTICAL PHASE CONJUGATION AMPLIFIER FOR REMOTE OBJECT TRACKING AND CHARACTERIZATION

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ABSTRACT

An active laser tracking system (ALTS) that performs pointing, tracking and characterization of a remote object, such as high-altitude aircraft, satellite, or reentry vehicle, requires a sufficient level of energy density delivered to its surface. Satisfactory performance of a proposed ALTS concept has been demonstrated previously at relatively short distances though severe atmospheric turbulence conditions [1]. Long range tracking for airborne and space objects with low intensity returned signal introduces serious challenges for an efficient and functioning ALTS. Solution to the two key technical challenges of (i) very low intensity of a returned signal; and (ii) compensation of optical aberrations along an extended beam path, is based upon the Brillouin Enhanced Four Wave Mixing (BEFWM) scheme. The results of analysis and experimental studies of the initial ALTS implementation illustrate that the BEFWM-based approach allows for an end-to-end solution to the problem of remote object pointing, tracking and characterization. Since the BEFWM approach provides a high-gain amplification of a weak coherent optical signal, this technique can also be used to reconstruct a coherent imaging of the remote object from its low amplitude wave function .

1. INTRODUCTION

The end-to-end solution to the laser system capable of reliably and steadily pointing and tracking remote (space or airborne) object must resolve the issues of delivering the laser beam with an optimal shape and maximized energy density to the object, as well as detecting the very weak scattered light from the object. Once detected and processed this signal will allow retrieval of the information required for object characterization to a level that is sufficient for its identification and track association. In the proposed ALTS operational scheme the focused laser beam delivered to the object over the long range can be viewed as an output signal, while the detected object-scattered light (OSL), i.e. the returned signal, will serve as an input signal. The interaction of laser beams with the propagation medium (atmosphere) and the remote object can be considered as the transformation mechanism to enable the derivation of the object characteristics from the measurement of OSL by data processing algorithms, including such critical parameters as its 3D state vector, velocity, maneuvering, coherent imaging [2], etc.

Two critical capabilities are essential to enable such an end-to end solution to a laser system for high accuracy pointing, tracking, and characterization of a remote airborne or space object from a ground based platform:

(i) Delivery of a sufficient level of energy to the object;

(ii) High-sensitivity detection of the returned signal.

Both capabilities are closely associated with the optical losses along the round trip between the ALTS platform and the remote object. Although various mechanisms, including light scattering (both Rayleigh and Mie) and absorption are responsible for the losses, atmospheric turbulence and the related laser beam distortions are the major factors. Laser beam propagation through the turbulent atmosphere causes strong aberrations of its wavefront, resulting in a significant increase of the beam spot size at the remote object plane, degradation of its shape, and substantial decrease of the returned signal intensity (up to -120 dB from a LEO satellite).

Coherent-optical detection of a low-intensity OSL requires a high-gain, nearly thresholdless amplifier with an ultra-narrow bandwidth. It can be achieved by using the BEFWM approach as the core of the system. An optical phase-conjugate amplifier (PCA) has the attributes that are best suitable for this purpose [3,4]. The BEFWM scheme using the PCA technique in a mirror configuration (PCMA) enables not only reliable detection of a low-intensity signal, but also real-time compensation of wavefront aberrations, and eventually reconstruction of the complete wave function of the returned signal. These functional capabilities are necessary for effective ALTS operations in maximizing the laser beam energy illuminating the remote space object for increasing the returned signal strength, and correcting the wavefront aberrations of the returned signal for enhancing the spatial resolution of the coherent imaging system [5]. In addition, the self-steering feature of the ATLS operation will keep up the laser beam pointing to the remote object continuously.

The results of the ground-to-ground field tests performed with the ALTS system built upon the coupled-cavities scheme [1] have proven the technical feasibility of this design concept. However, long range ground-to-space application imposes severe challenges in detecting, measuring and processing the returned signal that can be at as low as several hundreds of photons (10^{-16} J) per element of resolution. Solution to this problem by using the BEFWM based schemes have demonstrated that in addition to almost 100% fidelity in phase conjugate beam, it provides extremely high coherent amplification $\leq 10^7$. Combination of the techniques of high sensitivity ($\sim 10^{-15}$ J) and narrow spectral bandwidth $\leq$ 300 MHz (or $\leq$ 0.01 cm^{-1}) should allow significant enhancement of ALTS performance in terms of range and operational consistency. The specificity of the BEFWM operation places strict requirements to the laser system, especially taking into account that the BEFWM can be realized only with short laser pulses. This paper lays out a systematic approach for the development of the system that can satisfy such stringent capability requirements.

2. BEFWM-BASED OPERATIONAL SCHEMATIC FOR ALTS

Since the OSL serves as a signal beam for the BEFWM, the ALTS operation requires a laser beam with the matched carrier frequency. This is illustrated schematically in Fig. 1 that shows the ALTS operational principles. First the pilot laser Pulse 1 is sent out for target illumination. The OSL denoted as Pulse 2 is then picked up through Receiving Telescope and is directed towards Amplifier and BEFWM PCMA, with the latter being pumped by laser Pulse 3. After interacting with the BEFWM unit, the phase conjugated and amplified beam propagates reverse path to the object as Pulse 4. For the BEFWM to be effective and provide PCA with a maximal gain, arrival of the OSL and pumping pulses to the non-linear medium (NM) should be time-synchronized, and their frequencies matched as illustrated in Fig. 2. Meeting all these conditions is required for the system to sustain the lasing.

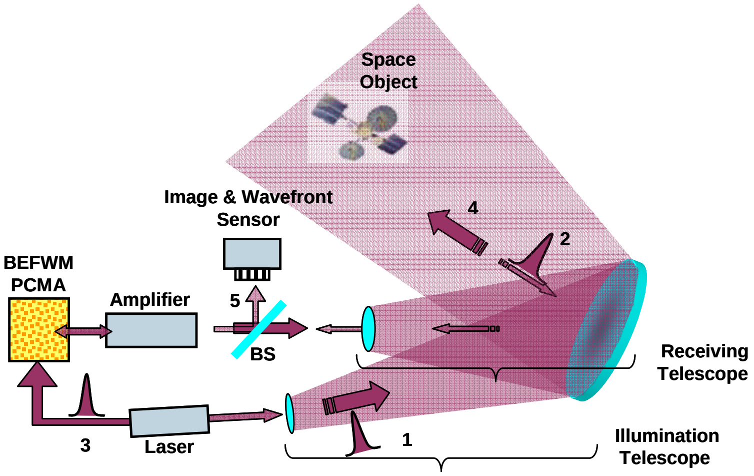

Fig.1. Operational principles of ALTS: Pulse 1 illuminates the target, and OSL 2 is captured by the Receiving Telescope. The OSL is then amplified and phase conjugated at BEFWM-based PCMA that is pumped by the laser pulse 3. On the return path the OSL is amplified again and goes back to the target (Beam 4). A small portion of this PC beam (Beam 5) reflected by beam splitter (BS) is fed into the set of imaging and wavefront sensors.

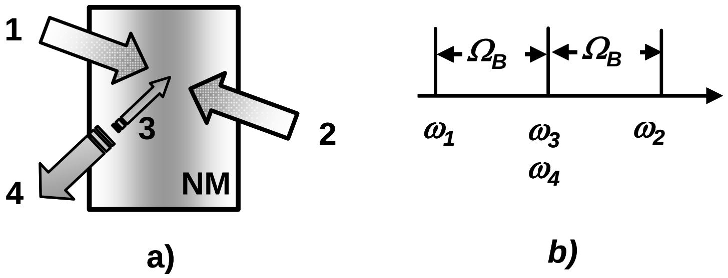

Fig.2. The BEFWM scheme in Brillouin-active nonlinear medium (NM). b). The pump Beams 1 and 2, and the signal Beam 3 have its carrier frequency shift on a Brillouin hyper-sound frequency (Ω_B). The frequency of the signal beam is Stokes-shifted relative to the pump Beam 2. Interaction of the Beams 2 and 3 generates spatial modulation of the NM refractive index (dynamic grating), and diffraction of the Beam 1 on this grating generates PC Beam 4.

3. GENERATION OF THE INTERACTING PULSES AT BEFWM

The proposed laser system must generate three pulses: the object illumination pulse and two pump pulses, and their carrier frequencies should match to account for the Brillouin shift in the phase conjugated signal (Fig. 2). For the remote object, the round trip delay-time of the signal pulse can be of the order of hundreds of microseconds to tenths of milliseconds. With an ultra-narrow bandwidth of the BEFWM (of the order of hundred of MHz) the laser system should generate a sequence of short, relatively high-energy (several hundreds of mJ) pulses with desired frequency shift. Such a laser system should operate in a seeded Q-switching regime. Conventional approach in achieving this operating regime is made by setting the Q-switched laser cavity matched to the seed frequency. This scheme however does not allow pulse generation at an arbitrary time, which equates to variable target positions and distances from the ALTS during its normal operation.

The solution to this problem is based on an analysis of the oscillation process of the Q-switched laser [6]. The main idea behind is as follows: the laser cavity for the pulse round trip should be filled with the radiation that essentially exceeds the level of spontaneous emission of the laser medium. In this case the carrier frequency of the lasing pulse is equal to that of the seeding pulse without any adjustment of the seeding wavelength to the longitudinal mode of the cavity. The optical set up of such a laser system is schematically shown in Fig. 3.

In this configuration, the ring laser cavity is formed by two polarization beam splitters (PBS) and two high reflection mirrors (M1,2). Q-switching regime is governed by two Pockells cells I and II (PC1 and PC2). Prior to applying the voltage to the Pockells cells the laser cavity remains open and seed light from the CW stabilized laser makes only one round trip through the cavity. By applying a short leading edge voltage pulse to PC1 there is a fast shut down of the cavity with its quality reaching its upper limit and simultaneously capturing the seed light that was present in the cavity. Once the energy of this intracavity pulse reaches its maximal value, the PC2 initiates cavity dumping and extracts the intracavity pulse.

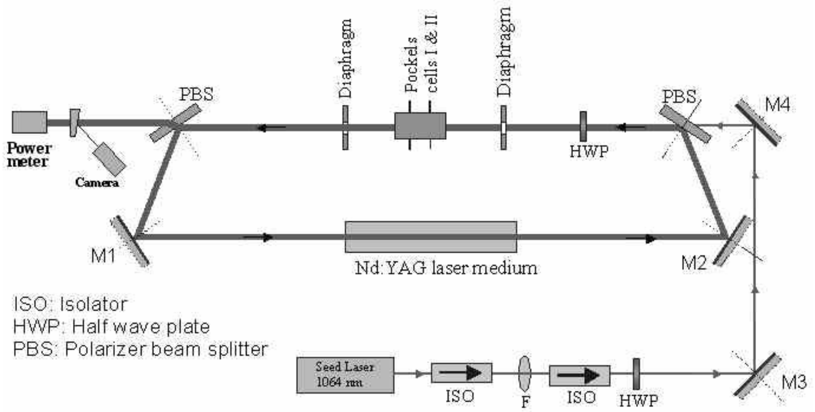

Fig. 3. Optical scheme of the seeded Q-switched laser.

Fig. 4 a) shows an example of the pulses of laser oscillation and voltages applied to the Pockels cells. Fig. 4 b) shows the Fabry-Perot interferogram of the oscillated pulse. The data shown in Fig. 4 clearly demonstrate that the proposed seeding methodology allows generation of the laser pulses with specified spectral characteristics at a chosen time. Thus the laser system guarantees the required spectral and temporal characteristics of the pulses for target illumination and pumping the BEFWM.

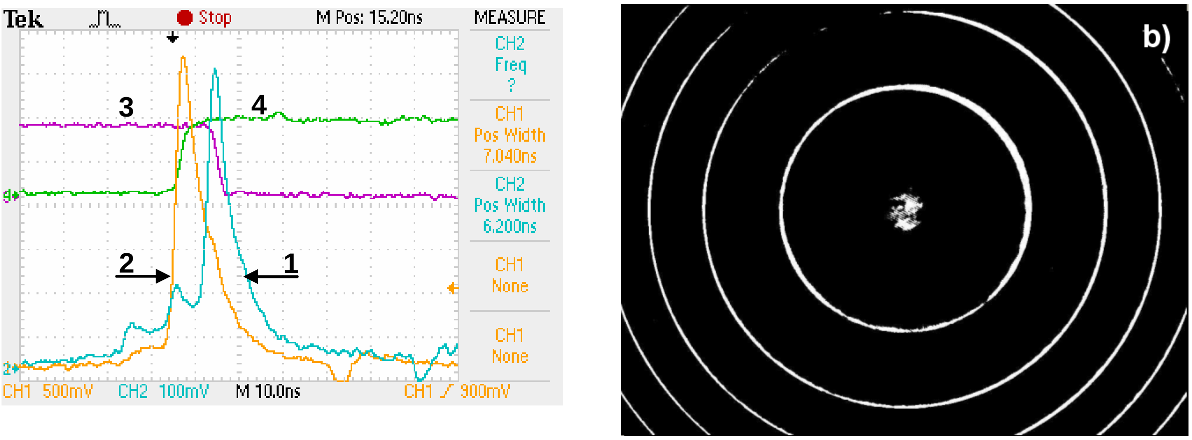

Fig.4. a). Traces of the laser pulses (1, 2) and voltages applied to the Pockels cells (3, 4). 1 is the intracavity oscillating pulse. 2 is the emitted laser pulse after the second Pockels cell is switched on (pulse 4). The pulse 3 shows the voltage applied to the first Pockels cell. b). Spectrum of the oscillated pulse taken by Fabry-Perot interferometer with the free spectral range 0.5 cm^{-1}.

As already has been discussed in this paper, realization of the ALTS requires two pumping pulses with their carrier frequency adjusted to the frequency of the signal pulse. This problem is solved by using three Q-switch lasers, which are seeded by the corresponding CW-seed lasers. The CW regime of these seed lasers enables controlling and tuning their wavelengths to satisfy matching requirements shown in Fig. 2. Such an approach allows to account for the Doppler shift in the light scattered by a moving object, and to adjust the wavelength of the pump beams for compensating this frequency shift. The Q-switch laser seeding doesn’t require the slave laser cavity modes matching to the seeding wavelength, thus enabling simpler synchronization of the signal and pumping pulses in a nonlinear medium. Therefore such configuration of laser wavelength seeding enables an autonomous oscillation of the illumination pulse and two BEFWM pump pulses.

4. CHARACTERISTICS OF THE BEFWM

It should be noted that the noise signal, with its frequency unmatched to the conditions optimal for a signal beam, has no influence on the performance of the proposed ALTS, This is because the spectral band of the noise signal does not match the gain bandwidth of the four-wave mixing process. Therefore, the only source of the noise on an angular element of resolution is the spontaneous Brillouin scattering of the pump beams. Consequently, the sensitivity of the PCM, at the condition of minimal energy of the signal beam $W_{\min}$ in a single spatial mode (on one element of the resolution), is:

$$W_{\min} = \hbar\omega \cdot \bar{n} \cdot \Delta f \cdot \tau / \eta \tag{1}$$

here $\hbar\omega$ is the photon energy; $\bar{n} = kT/\hbar\Omega$ ~ $10^3 - 10^4$ is the number of the thermal phonons at the hyper-sound frequency Ω_B in the NM at the temperature T; Δf is the gain bandwidth of the BEFWM; τ is the pulse duration of the scattered beam; and η is the quantum efficiency of the amplifier.

For the wavelength $\lambda = 1.06$ μm, and typical for these applications, using non-linear liquids with $\Omega_B = 2\times10^{10}$ rad/s:

$$W_{\min}\,[\mathrm{J}] = 5\times10^{-16}\, \Delta f \times \tau/\eta. \tag{2}$$

The magnitude of $\Delta f \times \tau/\eta$ depends upon the characteristics of the FWM. In the region of convective instability of BEFWM the dimensionless bandwidth $\Delta f\times\tau$ is determined by the duration of the pump beams and the stimulated Brillouin scattering (SBS) bandwidth (the magnitude of η can be assumed close to 1). In the region of absolute instability of the BEFWM the ratio is approximate: $\Delta f\times\tau \sim 1$. If the condition of equal pulse length for pump and signal beams is satisfied then $\eta < 1$. In an approximation of the square-wave interacting pulses of equal length, and with no saturation effects $1/\eta \cong G/4$, where $G = 25$ is the total increment of the stimulated Brillouin scattering SBS in the field of the counter propagating waves. It follows from Eq. (2) that the sensitivity of the BEFWM PCM is $W_{min} = 3\times10^{-15}$ J. These estimates allow a calculation of a minimal energy per element of resolution that can still be phase conjugated. By setting a quantum amplifier with an amplification ~ 10^3 prior to PCM, one can approximate that the minimal signal level that can be amplified is of the order of 10^{-18} J/mode or 10 photons per element of resolution [2].

The above described technique was applied to a BEFWM breadboard using the 30 cm long cuvette with Freon - C_8F_{18} as the NM. With the hyper-sound life-time $\tau = 1$ ns and the Brillouin frequency shift $\Delta\nu = 0.045$ cm^{-1} the SBS threshold in a single mode beam is equal to $W_{SBS} = 1.9$ mJ and the gain g = 6.5 cm/GW. The maximum energy of the pumping beams was 150 mJ each. With such parameters this BEFWM was able to achieve amplification of the PC pulse up to 60 dB in peak power and 50 dB in the pulse energy with input pulse energy ~ 1 nJ. Fig. 5 shows pulse's oscillograms of the four interacted beams.

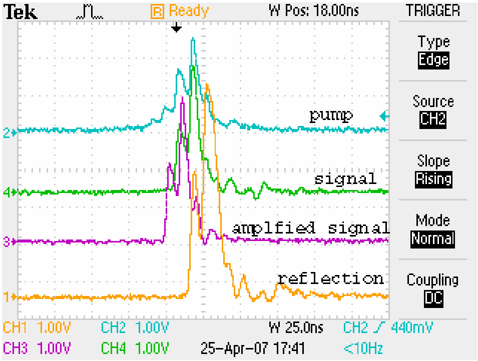

Fig.5. Traces of the laser pumping pulse, signal, amplified signal and phase conjugated beam.

Fig. 5 shows typical effect of compensating the phase aberration by the BEFWM mirror, illustrating an example of a high fidelity of the phase conjugation with signal amplification.

5. CONCLUSION

In this paper we discuss the approach in developing the ALTS system capable of robust pointing, tracking and characterization of a remote object. Previously we demonstrated the unique capabilities in ground-to-ground field test of this system. With its design based upon coupled-cavities laser configuration, the ALTS performed reliable detection of the signal from the object at the distance about 6.4 km. The BEFWM-based detection technique described in this paper demonstrates the feasibility of much higher sensitivity due to its thresholdless operation. The output of this system is an amplified and phase conjugated signal beam that holds the complete information of the object-scattered wave function, which is essential for remote object characterization (Section 2). Furthermore, due to the coherent nature of detection, the proposed technique enables characterization of the atmosphere-aberrated wavefront and provides data for its real-time compensation (Section 2). The system analysis and results of initial experiments demonstrate the feasibility of BEFWM technique as a key component of an end-to-end solution to the problem of a remote object tracking and characterization (Section 3 and 4). The BEFWM-based design of the ALTS enables the following operations that are essential for a reliable long-range tracking and pointing: formation of a high-quality laser probe beam on the remote object, coherent detection of the object scattered light, and amplification of this detected signal to the level sufficient for detailed characterization of the object.

6. ACKNOWLEDGEMENTS

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