

New Self-Adaptive Source and Sensor Technologies for Enhanced Remote-Sensing

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Abstract

We describe the latest developments of new sensor and source device technologies based on novel adaptive holographic techniques. This new technology offers enhanced capabilities for remote sensing. The innovative adaptive holographic techniques are based on nonlinear saturable gain in laser amplifier media allowing real-time response for acquiring signals corrupted by distortion. The adaptive sensor is demonstrated to perform time-resolved optical metrology with speckle-distorted beams. Experimental results are in agreement to analytical theoretical calculations. An adaptive high power solid-state laser source is demonstrated to maintain high beam quality TEM₀₀ and single frequency despite severe amplifier thermal distortion and cavity perturbation. Operation of the adaptive laser to nearly 100W average power level has been achieved. Most recently, this technology has been demonstrated to operate in a pulse format with very short pulses (<3ns) whilst maintaining single spatial and spectral mode operation.

Introduction

This programme has advanced new capabilities for remote sensing by using real-time gain holography techniques. Experimental results are presented of adaptive interferometric sensors for extraction of target motion (e.g. vibration) from a speckle-degraded optical signal beam (e.g. due to atmospheric turbulence, surface roughness, misalignment) and also of self-stabilising adaptive laser sources that provide rugged high power TEM₀₀ CW and pulsed sources by self-correction of amplifier thermal distortions and external perturbations.

1. Adaptive Gain Interferometric Sensor

Optical metrology using interferometric sensing is a very powerful tool for remote measurements of object information (e.g. vibration, velocity and distance) with high temporal and spatial resolution. A serious problem for interferometry in real-world

applications, however, is spatial degradation of the optical probing beam due to roughness or non-uniformity of the object surface or path distortions, such as atmospheric turbulence, leading to speckle formation [1]. Spatial degradation leads to significant reduction in the beam coherence and, together with misalignment, destroys the quality and strength of signal from the interferometer about the object information of interest.

Our adaptive sensor device is termed as an adaptive gain interferometer (AGI) in which the formation and replay of a saturable gain hologram in a laser amplifying medium allows coherent beam coupling between a speckle distorted object beam and a reference beam. The principle of the AGI is depicted in Fig.1 showing the intersection of two coherent fields (reference beam E_1 and object beam E_2) inside a laser amplifier medium.

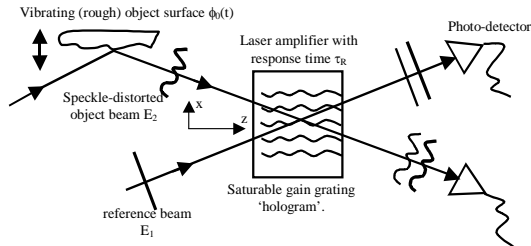


Figure 1. Adaptive gain interferometer (AGI) shown applied to vibrometry

The periodic intensity interference pattern spatially-modulates the gain coefficient – forming a volume gain hologram [2]. The output field after length L of gain medium is $A_1(L) = A_1(0) \cdot t_a + A_2(0) \cdot r$, with t_a is a transmission (gain) term and r is a diffraction term of the other beam from the gain hologram. The output field is a summation of an amplified transmission term ($t_a \cdot A_1(0)$) and a holographic diffractive term ($r \cdot A_2(0)$) that are self-aligned and wavefront matched (see Fig. 1). For slow phase changes in object beam, including time-varying speckle, the gain hologram can adapt and maintain fixed phase difference between these two terms. However, due to finite response time of the gain hologram formation, fast vibrational changes lead to intensity changes in the output intensity that a photodetector can measure.

Fig.2 shows an experimental adaptive gain interferometer (AGI)

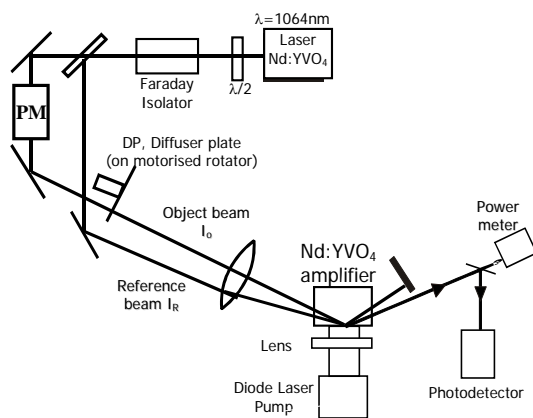


Figure 2. Experimental adaptive gain interferometer (AGI) system.

A continuous wave Nd:YVO₄ laser is split into two beams to form an object beam and a reference beam. A diode-pumped Nd:YVO₄ slab laser amplifier is a high gain “bounce” geometry. The reference and object beam overlap to form a gain hologram. The incident object and reference beams were made approximately equal in power at $P_O=P_R=1\text{mW}$, to achieve good, but not excessive, saturation of the amplifier. A phase modulator (PM) provided a sinusoidal phase modulation $\phi(t)$ of the object beam to simulate a vibrating surface reflection. To perform a controlled frequency test of the AGI response we varied the phase modulator frequency (f) and the results are shown as the upper curve in Fig. 3 with no aberrating diffuser plate (DP) in the object beam arm. The results are in good correspondence to theory prediction. We measure a compensation (mid-point) frequency of approximately 3kHz.

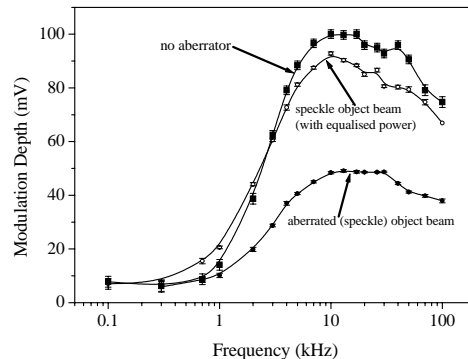


Figure 3. Experimental AGI frequency response: a) object beam without aberrations; b) speckle aberrated object; and c) aberrated speckle object beam with two-fold incident power.

The frequency response of the AGI, when the object beam was speckle aberrated (by a diffuser plate), is shown in the lower curve in Fig. 3. It is almost identical in shape to the case without speckle except for reduced amplitude \sim times two. caused by the diffractive loss of the object beam at the amplifier. It can be offset by

increasing the incident power of object beam incident on the diffuser plate by a factor of two as seen in the upper speckle curve in Fig. 3.

A further scheme has been tested whereby the amplified reference beam is sent to a target and the reflection back through the amplifier modulates the reference beam. This system has greater simplicity, compactness and works with low reflectivity from the target than the above system. Recent results suggest that this geometry can also detect low frequency signal information $<3\text{KHz}$.

2. Adaptive Laser Sources

In high power solid-state lasers thermally-induced distortion effects lead to degradation of spatial beam quality and impair cavity stability and laser efficiency. We have performed investigations of adaptive laser sources (seeded and self-starting) that can self-compensate for the distortions and maintain high spatial and spectral stability even at high pump levels. The adaptive compensation is performed by the generation of dynamic gain holograms in the laser amplifier by using self-intersecting loop geometry [3,4]. The hologram encodes the distortions and oscillation (replay) from the hologram forms a distortion corrected output beam.

2a. Seeded Adaptive Laser Source

Fig. 4 shows the experimental seeded adaptive laser source using a diode-pumped Nd:YVO₄ laser amplifier. A seed laser at 1064nm injects 6mW of TEM₀₀ single frequency input power into the loop. The distortion corrected output of the adaptive laser is in the direction P_{PC}.

Fig. 5 shows a graph of the generated PC output power against pump power. A phase conjugate (PC) power of about 24 W with 80 W pumping was achieved (30% efficiency).

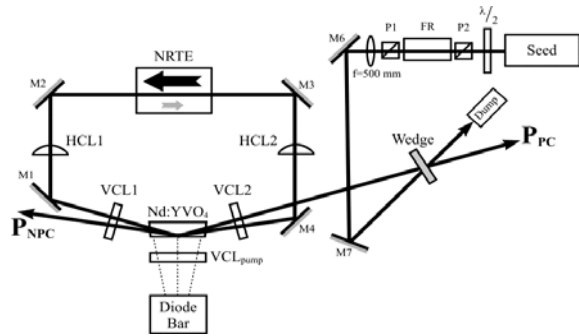


Fig. 4: Diagram of seeded adaptive laser

For the 6mW input, this output represents $\sim 4000\times$ amplified output. Spatial performance was of a very high quality TEM₀₀ mode with beam quality measurements of the giving an $M^2 < 1.2$. The non-phase conjugate output P_{NPC} from the rear of the loop laser system is shows beam distortion. This illustrates the adaptive correction (phase conjugation) of the spatial mode.

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Fig. 5: Adaptive laser output power P_{PC}, spatial quality (TEM₀₀) and single frequency

2b. Self-starting Adaptive Laser Source

By replacing the seeding laser by a mirror (OC) that provides feedback a self-starting version of the above adaptive laser was produced with self-organised formation of an adaptive laser mode (see Fig. 6).

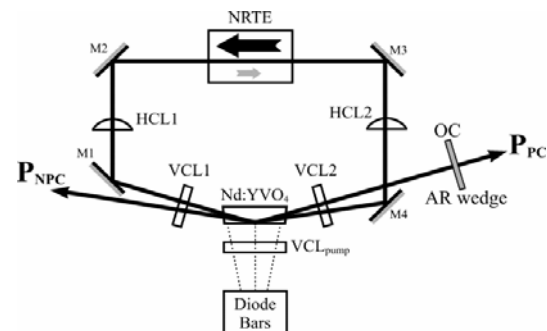


Fig. 6: Schematic diagram of self-starting adaptive laser source

A maximum output power of 24 W with 80 W pumping was achieved (30.8% efficiency). Spatial performance was of a

very high quality TEM₀₀ with measured beam quality M^2 horizontally < 1.2, and vertically < 1.1. Spectrally narrow single longitudinal mode performance was achieved. Power scaling of the adaptive laser was performed by placing a second diode-pumped Nd:YVO₄ amplifier in the output coupler arm. Figure 7 shows the output power of the adaptive laser against amplifier pump power. Over 90W output power was achieved. The system has been recently run in a self-Q-switched pulsed mode. In this scheme the diode is run in a pulsed QCW regime with pulsed operation up to 1kHz. Pulses as short as 2.7ns have been generated. Single frequency and TEM₀₀ spatial mode was maintained. High pulse energy ~6mJ and ~ 1MW peak power was achieved.

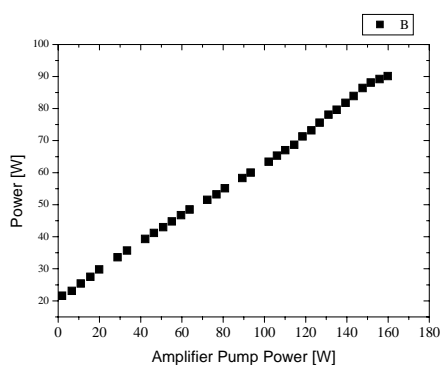


Fig. 12: Output power of adaptive source with secondary cavity amplifier

Conclusions

We have shown the adaptive gain interferometer (AGI) provides a novel capability for real-time extraction of

temporal object information despite the presence of severe speckle spatial distortion, with self-alignment and use of a simple, low-cost detection system.

Seeded and self-starting adaptive lasers sources were constructed. Excellent correction and maintenance of TEM₀₀ beam quality and single frequency was obtained. Operation of the adaptive laser system to over 90W power level was achieved. Pulsed operation with pulse duration 2.7ns and high pulse energy 6mJ and high peak power 1MW was achieved. Such systems show good promise for enhanced remote sensing systems, particularly if the technology can be adapted to the eye-safe wavelength regime.

References

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