

# Self-Optimising Sensors and Sources for Remote-Sensing

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## Abstract

*We describe the development of new sensor and source devices offering enhanced capabilities for remote sensing. These systems make use of innovative adaptive holographic techniques in laser gain media. Experimental results are presented of an adaptive sensor and an adaptive laser source. The adaptive sensor is demonstrated to perform time-resolved optical metrology with speckle-distorted beams. An adaptive high power solid-state laser source is demonstrated to maintain high beam quality TEM<sub>00</sub> 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.*

Keywords:

## Introduction

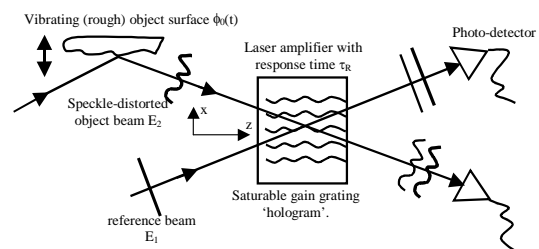
We report new capabilities for remote sensing by using real-time gain holography techniques. In particular, we present results of (i) adaptive interferometric sensors for extraction of target motion (e.g. vibration) from a speckle-degraded optical signal beam (e.g. due to atmospheric turbulence, rough surface, misalignment) and (ii) self-stabilising adaptive laser sources that provide rugged high power TEM<sub>00</sub> 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.

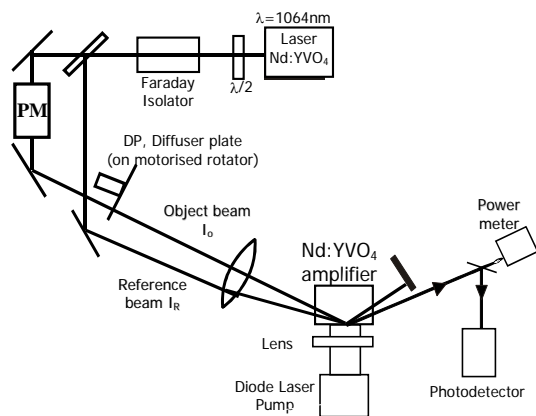
Our adaptive sensor device is termed as an adaptive gain interferometer (AGI) in which the formation and replay of a saturable gain hologram in a laser amplifying medium allows coherent beam coupling between a speckle distorted object beam and a reference beam. The principle of the AGI is depicted in 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]. Under the approximation of weak saturation ( $I/I_s \ll 1$ ), the output field after length  $L$  of gain medium is  $A_1(L) = A_1(0).t_a + A_2(0).r$ , 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 ( $t_a.A_1(0)$ ) and a holographic diffractive term ( $r.A_2(0)$ ). These two terms are self-aligned and wavefront matched (see Fig. 1). For any slow phase changes in the object beam, including spatially varying speckle, the gain hologram can adapt and maintain fixed phase difference between these two terms. However, due to the finite response time of the gain hologram formation, fast vibrational changes will change the phase relationship and lead to intensity changes in the output intensity  $I_1(L,t)$ , and this can be measured by a photo-detector.

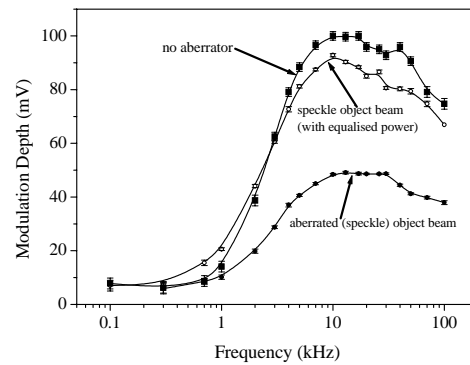
An experimental adaptive gain interferometer (AGI) was constructed and is shown schematically in Fig. 2.



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

A continuous wave Nd:YVO<sub>4</sub> laser is split into two beams to form an object beam and a reference beam. A diode-pumped Nd:YVO<sub>4</sub> slab laser amplifier in a

“bounce” geometry was used as the saturable gain medium. 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 ~ 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.

## 2. Adaptive Laser Sources

In high power solid-state lasers heat 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:YVO<sub>4</sub> laser amplifier. A seed laser at 1064nm injects 6mW of TEM<sub>00</sub> single frequency input power into the loop. The distortion corrected output of the adaptive laser is in the direction P<sub>PC</sub>.

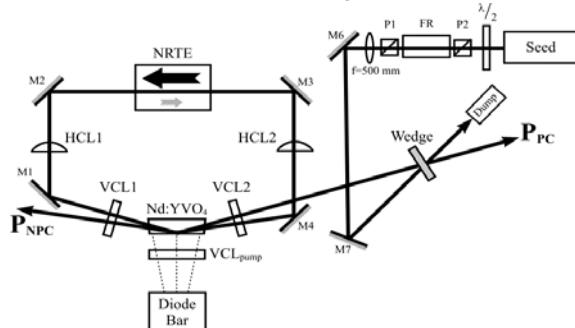


Fig. 4: Schematic diagram of seeded adaptive laser

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 corresponding to about 30% optical-to-optical efficiency. For the 6mW input, the 24W output represents an amplified output of ~ 4,000 times.

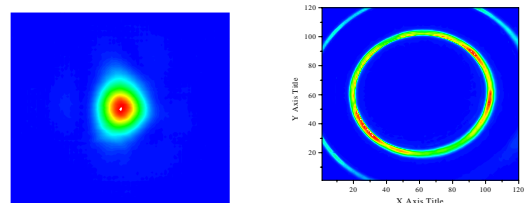
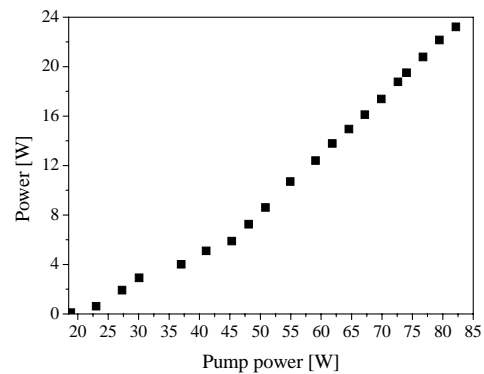
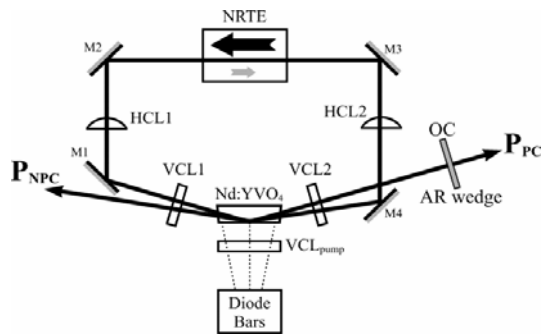


Fig. 5: Experimental output power P<sub>PC</sub> and spatial quality (TEM<sub>00</sub>) and single frequency FP pattern of seeded adaptive laser

Spatial performance was of a very high quality TEM<sub>00</sub> mode as seen in Fig. 5 with beam quality measurements of the giving an  $M^2$  horizontally < 1.2, and vertically < 1.1. The non-phase conjugate output P<sub>NPC</sub> from the rear of the loop laser system is shows beam distortion. This illustrates the adaptive correction (phase conjugation) of the spatial mode. The non-PC power was less than 1W at pump power of 80W.

### 2b. Self-starting Adaptive Laser Source

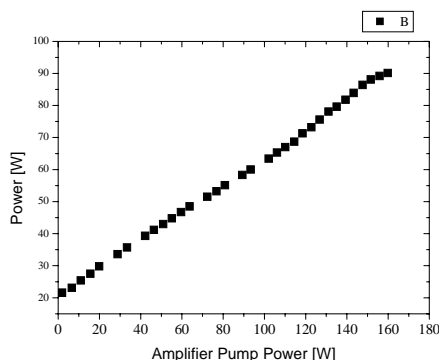
By replacing the seeding laser by a mirror (OC) that provides feedback a self-starting version of the above adaptive laser was produced with self-organised formation of an adaptive laser mode (see Fig. 6).



**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 TEM<sub>00</sub> 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:YVO<sub>4</sub> 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.



**Fig. 7: Output power of self-starting adaptive source with secondary amplifier in cavity**

## 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. Object information is accessed with minimal loss of performance and with self-alignment and use of a simple, low-cost detection system.

Seeded and self-starting adaptive lasers sources were constructed with correction of severe thermally induced distortions and lensing in the laser amplifier. Excellent correction and maintenance of near diffraction-limited TEM<sub>00</sub> beam quality and single frequency was obtained. Operation of the adaptive laser system to over 90W power level was achieved.

## References

- 1 *Selected papers on speckle metrology*, (R.S. Sirohi, editor), SPIE milestone series, vol. MS35, 1991.
- 2 M.J. Damzen, Y. Matsumoto, G.J. Crofts and R.P.M. Green, *Opt. Commun.*, 123, 182 (1996)
- 3 M.J. Damzen, M. Trew, E. Rosas and G.J. Crofts, *Opt. Commun.*, 196, 237 (2001)
- 4 M.Trew et al, *Opt Lett.* 25, 1346 (2000)

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