Detection of Laser Induced Gratings via Acoustic Enhancement *

Truman D. Black and Don A. Larson **

Department of Physics, The University of Texas at Arlington,
P.O. Box 19059, Arlington, Texas 76019, USA

Using acoustic wave intermodulation, laser induced grating structures can be detected with enhanced sensitivity. Gratings with phase variations of the order of a few µrad or displacement gratings of the order of 10^{-13} m can be detected. The basic spatial frequency analysis explaining this detection enhancement is developed briefly in this paper.

1. Introduction

Experiments to detect laser induced damage, thermal gratings, and surface waves lead to an elegant diffraction theory based on a spatial frequency analysis of propagating laser beams. This spatial frequency analysis has been developed into a general approach to study a variety of diffractive structures including holograms and photorefractive gratings [1–3].

The analysis incorporates the fundamental concepts of the superposition of plane waves and spatial frequency spectra. Only the simplest proximity case is presented here. That is, a propagating probe beam interacts with a laser induced grating and a spatially separated traveling acoustic wave. For the analysis, both the induced and traveling gratings are considered to be infinite in extent, so that edges and beam shape can be neglected. Additionally, the acoustic grating is assumed parallel to the induced grating and to have the same spatial period, $\Lambda = b$. The spatial frequency components of both gratings are then harmonically related. Furthermore, the major temporal modulation term of the intensity in the resulting diffracted beams is at the same frequency as the acoustic wave. The excellent sensitivity and selectivity are achievable due to this "tuned" coherent intermodulation between the spatial phases of both gratings.

2. Analysis

For the tuned case of interest here, both structures have the same period and corresponding spatial frequency $\xi_1 = 1/\Lambda = 1/b$. The spatial frequency spectrum of the laser induced grating is the superposition of harmonically related delta functions given by

$$A_G(\xi) = \sum_{k=-\infty}^{k=+\infty} a_k \delta(\xi - k\xi_1), \qquad (1)$$

where a_k is the kth Fourier coefficient of the induced grating. The corresponding spectrum of the traveling acoustic wave is similar except that it oscillates at harmonics of the fundamental frequency of the acoustic wave, Ω:

$$A_W(\xi, t) = \sum_{n=-\infty}^{n=+\infty} J_n(\phi_s) \exp\{-in\Omega t\} \delta(\xi - n\xi_1), \quad (2)$$

where $J_n(\phi_s)$ is the nth Bessel function of the first kind and ϕ_s is the modulation amplitude of the traveling acoustic grating.

The basic probing arrangement is illustrated schematically in Figure 1. The probing beam is considered as a normally incident plane wave, $\delta(\xi)$, so the resulting diffraction from the induced structure is simply the grating spectrum given by (1). The propagation between the induced grating structure and the traveling acoustic grating is represented by a space transmission function

$$T(\xi) = \exp\{-i\pi\xi^2\lambda L\}, \qquad (3)$$

where λ is the probing beam's wavelength and L is the separation distance between the grating structures. $T(\xi)$ is essentially equivalent to a Fresnel propagator.

The superposition of the plane waves incident on the traveling grating, $T(\xi) A_G(\xi)$, is diffracted further
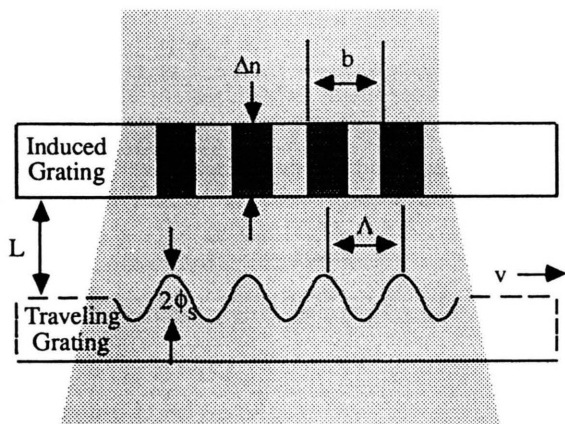

Fig. 1. Schematic illustration of acoustically enhanced laser probing configuration.

by the acoustic grating. The resulting diffraction spectrum is found by convolution:

$$S_T = A_W(\xi, t) \otimes T(\xi) A_G(\xi). \qquad (4)$$

This output spectrum contains plane waves with spatial frequencies determined by the diffraction orders, m, which are also harmonically related for the "tuned" case. So then,

$$S_T = \sum_{m=-\infty}^{m=+\infty} A_m(L, t, \Omega, \phi_s, a_k) \delta(\xi - m\xi_1). \qquad (5)$$

Information about the laser induced gratings, the acoustic grating, and their separation is carried in the spatial amplitude coefficients. Detailed analysis allows the retrival of this information. Experimentally, with a lens and a slit aperture, a single spectral order of
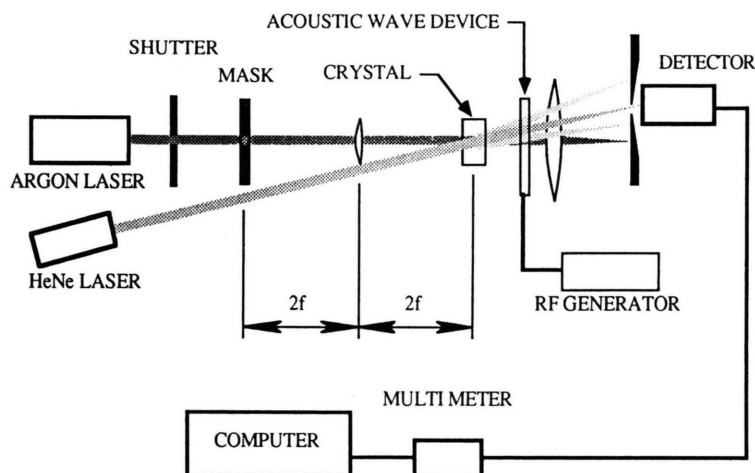

Fig. 2. Experimental schematic of the acoustically enhanced probing system for studying laser induced photorefractive gratings.
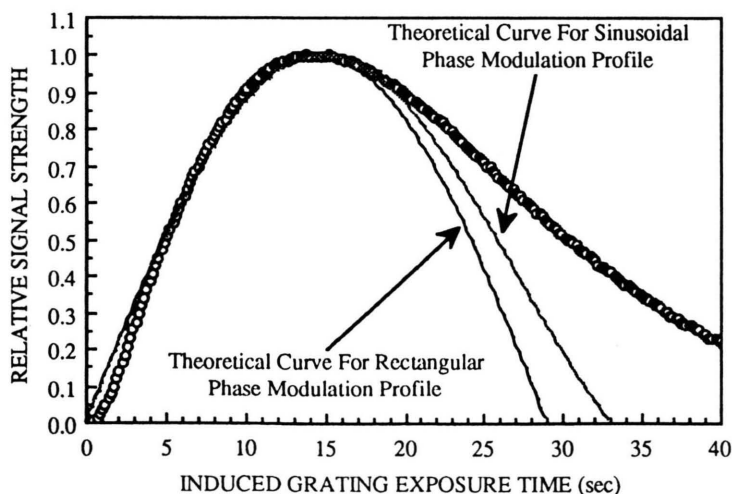

Fig. 3. Comparison of theoretical curves for induced gratings of sinusoidal and rectangular phase profiles with the experimentally detected signal as a function of induced grating exposure time.

intensity $G_m = A_m^* A_m$ can be isolated. The detected intensity modulation of that order can be filtered electronically and the signal oscillating with frequency Ω, $G_m^{(\Omega)}$, analyzed. For example, for an induced phase grating of modulation amplitude, $\phi_I (\Delta n)$, the intensity modulation in the undiffracted zero order is of the form

$$G_0^{(\Omega)} \propto a_0 (\phi_I) a_1 (\phi_I) \cos (\pi \lambda \xi_1 L) \cos (\Omega t). \quad (6)$$

The signal is periodic in the separation, L, between the induced grating and acoustic reference grating. This periodic behavior is an important feature of the theory and has been confirmed experimentally [3]. It also permits the induced grating experiment to be conveniently separated from the traveling acoustic reference structure without loss of sensitivity. In the small signal limit $a_0 \sim 1$, $a_1 \sim \phi_I$ and the oscillating signal is linear in the induced grating's modulation amplitude. Without this enhancement, the diffraction effects are second order.

3. Experimental Applications

Figure 2 shows schematically the experimental configuration for investigating laser induced photorefractive gratings.

Figure 3 compares theoretical curves from the above analysis with experimental data for a laser induced grating. The induced grating was produced by projection recording in $Fe:LiNbO_3$, which is photorefractive [4]. The analysis assumes that the induced phase modulation increases linearly with laser exposure time.

The first order sensitivity of the probing technique is clearly illustrated. This enhanced sensitivity permits the investigation of extremely small laser induced effects.

[1] T. D. Black and V. A. Komotskii, Appl. Phys. Lett. **38,** 113 (1981).
[2] R. Magnusson and T. D. Black, J. Opt. Soc. Amer. A **4,** 498 (1987).
[3] D. A. Larson, T. D. Black, M. Green, R. G. Torti, Y. J. Wang, and R. Magnusson, J. Opt. Soc. Amer. A **7,** 1745 (1990).

[4] T. D. Black, A. Hafiz, D. A. Larson, and R. Magnusson, Appl. Phys. Lett. **55,** 2392 (1989).