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Low-Coherence light source design for ESPI in-plane displacement measurements

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A R T I C L E I N F O

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A B S T R A C T

The ESPI method for surface deformation measurements requires the use of a light source with high coherence length to accommodate the optical path length differences present in the apparatus. Such high-coherence lasers, however, are typically large, delicate and costly. Laser diodes, on the other hand, are compact, mechanically robust and inexpensive, but unfortunately they have short coherence length. The present work aims to enable the use of a laser diode as an illumination source by equalizing the path lengths within an ESPI interferometer. This is done by using a reflection type diffraction grating to compensate for the path length differences. The high optical power efficiency of such diffraction gratings allows the use of much lower optical power than in previous interferometer designs using transmission gratings. The proposed concept was experimentally investigated by doing in-plane ESPI measurements using a high-coherence single longitudinal mode (SLM) laser, a laser diode and then a laser diode with path length optimization. The results demonstrated the limitations of using an uncompensated laser diode. They then showed the effectiveness of adding a reflection type diffraction grating to equalize the interferometer path lengths. This addition enabled the laser diode to produce high measurement quality across the entire field of view, rivaling although not quite equaling the performance of a high-coherence SLM laser source.

1. Introduction

Electronic Speckle Pattern Interferometry (ESPI) is a versatile and highly sensitive optical method for determining surface displacement fields [1]. Depending on the setup geometry, the measurement sensitivity can be in-plane, out-of-plane, or a combination. The in-plane ESPI configuration uses an expanded, collimated laser beam that is divided into two paths to illuminate the object surface symmetrically at oblique angles. The light scattered from the optically rough object surface forms an interference speckle pattern that is observed by a camera. In-plane surface motions of the measured object cause relative changes in the optical path lengths of the two illumination paths, thus causing relative phase differences and corresponding changes in the observed interference patterns. Measurements of the interference patterns are made before and after object deformation, from which the distribution of surface displacements can be evaluated.

The oblique illumination angles cause substantial path length differences across the illuminated region on the specimen, typically ranging up to several centimeters. Consequently, the illumination source must have significant coherence length so that the interference can be observed effectively. The required high-coherence lasers tend to be large, delicate and expensive. These undesirable characteristics have tended to confine ESPI measurements mainly to the laboratory environment. However, many interesting and commercially promising measurement applications, for example on gas and oil pipes [2] and large composite structures [3], require the use of a portable instrument. In addition, attachment of the measurement instrument directly to the object can minimize the impact of environmental disturbances. Laser diodes have many characteristics that make them attractive for field measurements, notably their compact size, mechanical rigidity, low power requirements and modest cost. Unfortunately, they generally have a broad wavelength emission spectrum with limited coherence length, typically in a range of ~1 mm. Some specialized, high coherence laser diodes do exist [4], but are less readily available and have much higher cost than conventional laser diodes.

An alternative approach is taken here to overcome the coherence length limitation. Instead of seeking substantial laser coherence length, the aim is to eliminate the path length differences that arise within an in-plane interferometer. If the path lengths can be equalized, it would be possible to make practical measurements using a conventional low-coherence laser diode. Such equalization can be achieved using a transmission type diffraction grating [5,6]. This allows a symmetrical optical geometry. A significant concern, however, is the low intensity of the

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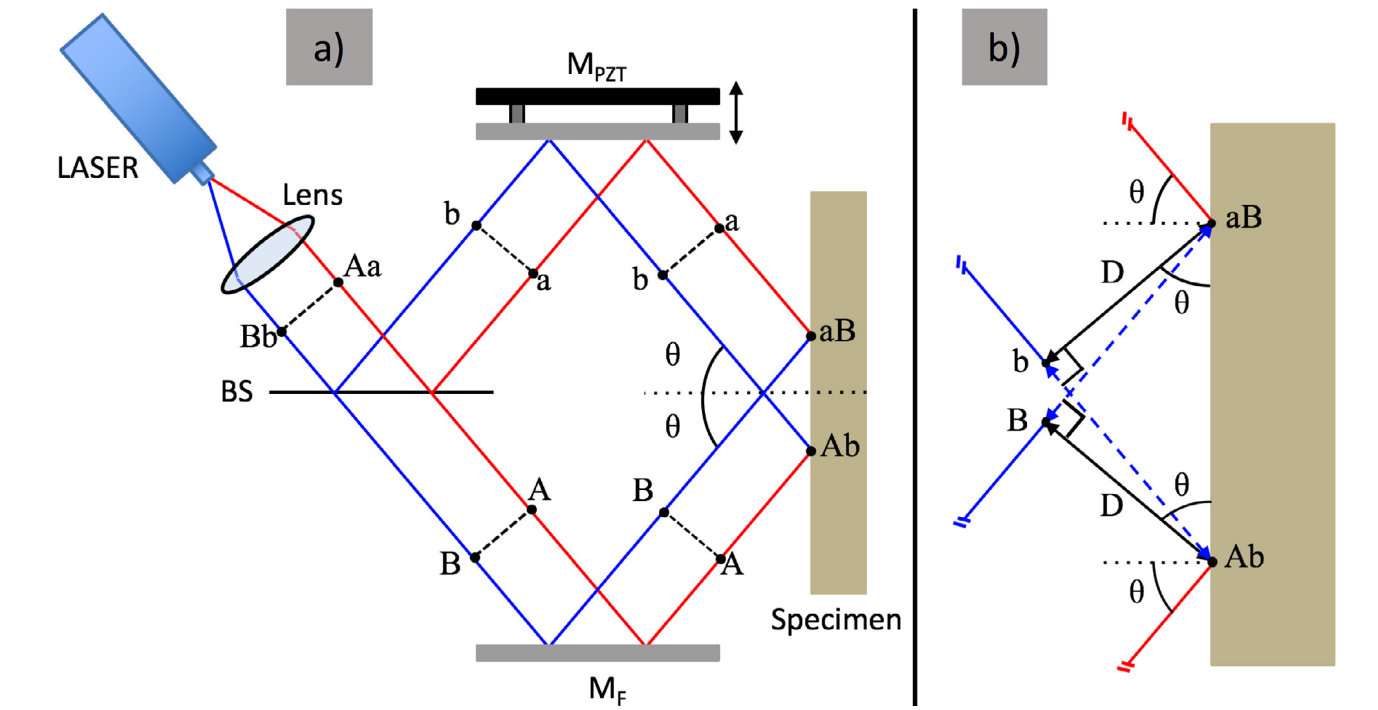

Fig. 1. Illustration of light propagation and path length differences in a conventional beam-splitter type in-plane ESPI. (a) Overall view, (b) detail view at specimen surface. The dashed black lines indicate the timefronts. BS = beam splitter, M_F = fixed mirror, and M_{PZT} = piezo mirror, D = beam diameter.

diffracted light, typically about 20–30% of the incident light. In this study, an alternative optical arrangement is proposed using a reflection type diffraction grating so as to benefit from the higher diffraction efficiency of this grating type and thereby to reduce the power requirements on the illumination source.

2. Path length compensation using a diffraction grating

Fig. 1 shows the light propagation in a conventional in-plane ESPI interferometer. An expanded, collimated light beam is divided into two paths using a beam splitter. Each beam is then directed to the object surface using a mirror. One of the mirrors has a piezoelectric actuator to allow local phase angle measurements to be made using the phase stepping method [7].

To understand the effect of limited coherence, it is necessary to consider the timefronts of the illumination light in addition to the wavefronts. The term "timefront" is used here to describe the instantaneous position of the light that originated from the source at a given time instant. For the traditional ESPI setup shown in Fig. 1, the timefronts coincide with the wavefronts. However, because of the oblique illumination, the timefronts, illustrated by the black dashed lines, do not arrive simultaneously at the object surface. Consequently, the optical path length L between the source and the specimen varies with spatial location on the object. For light beams with diameter D and illumination angle θ, the maximum optical path length differences ΔL across the object surface are:

$$\Delta L_{ab} = L_b - L_a = D\tan(\theta) \tag{1}$$

$$\Delta L_{AB} = L_B - L_A = D\tan(\theta) \tag{2}$$

Typically, the interferometer arms are adjusted so that the optical path lengths at the center of the illuminated region are equal. However, the path lengths vary linearly with transverse position, reaching $\pm D\tan(\theta)$ at the edges of the illuminated area. This variation in path lengths sets a requirement for a laser source of sufficient coherence

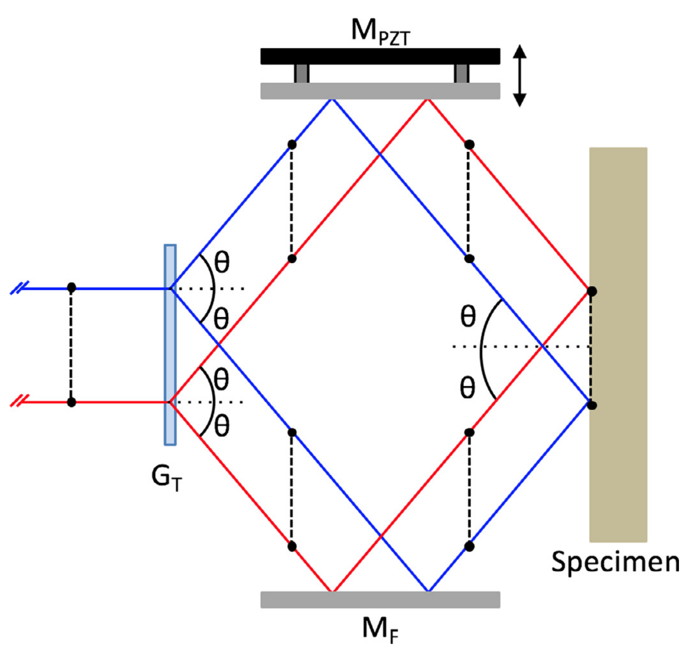

Fig. 2. In-plane ESPI interferometer using a transmission type diffraction grating. The dashed black lines indicate the timefronts, G_T = transmission grating, M_F = fixed mirror, and M_{PZT} = piezo mirror.

length to enable practical interference measurements. In this circumstance, conventional laser diodes cannot typically be applied.

Previous approaches to overcome the path length difference problem involved replacing the beam splitter in Fig. 1 with a transmission type diffraction grating to create the arrangement shown in Fig. 2 [6]. For normal light incidence, the diffraction angles θ_m for diffraction orders m depend on the grating line spacing d_g and light wavelength λ