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Dual-probe laser interferometer for structural health monitoring (L)

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In this note we present the development of a dual-probe laser interferometer that uses the filtering properties of a polarized beamsplitter to enable two independent (uncoupled) detection probes. The robustness of this system is demonstrated by making broadband, noncontact, high fidelity measurements of Lamb waves in an aluminum plate. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2170442]

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I. INTRODUCTION

Recent developments in quantitative structural health monitoring have presented the need for the measurement of the frequency-dependent attenuation and velocity of guided ultrasonic Lamb waves that propagate in plate-like components. These Lamb waves are dispersive and multimode, so it is advantageous to utilize the point-like, high fidelity, and noncontact nature of laser interferometry in their detection. Of particular importance is the ability to simultaneously measure the same Lamb wave at two different spatial locations. This ability to detect the same (dispersive) Lamb wave at two different propagation distances is critical for attenuation and scattering applications, which require an absolute comparison of frequency-dependent amplitudes, as a function of the spatial location. For example, Benz *et al.*[1] developed a correlation procedure to locate and size a notch in a plate by comparing the reflected and transmitted Lamb wave fields.

Existing dual-probe interferometer designs either use the reference beam and the object beam as the two individual probes to make a differential measurement,[2–5] or simply combine the components of two (independent) single-probe interferometers.[6] The multimode and dispersive nature of Lamb waves complicates their interrogation with a differential measurement system; since a time-domain Lamb wave signal is relatively long, the (optical) signals from the (coupled) reference and object beams can interfere with each other, causing spurious results in the Lamb wave signal. In contrast, in this note we present a dual-probe laser interferometer that provides the following advantages: *two independent (uncoupled) simultaneous measurements*; *and a reduced number of optical components*.

II. DEVELOPMENT OF THE DUAL-PROBE INTERFEROMETER

First consider the single-probe heterodyne interferometer shown in Fig. 1 that was developed in Bruttomesso *et al.*;[7] note that readers interested in more details on laser interferometry should see Scruby and Drain.[8] An argon-ion (continuous wave) laser generates a single beam of vertically polarized laser light (wavelength of 514.5 nm). The beam passes through an acousto-optic modulator (AOM) that splits this original beam into an infinite number of separate beams. Each beam has its frequency shifted by a specific frequency (40 MHz in this case), known as the beat frequency. The zeroth-order (unshifted) beam and the first-order (shifted) beam contain approximately 95% of the power from the original incident beam, and these are the only two beams used in this interferometer. The first-order beam eventually reflects off the specimen (object) surface, and is referred to as the object beam. The zeroth order beam (which passes to the photodiode without ever reflecting off the specimen surface) is referred to as the reference beam.

After leaving the AOM, the vertically polarized object beam passes through a polarized beamsplitter (PBS). The PBS causes vertically polarized light to be reflected at 90°,

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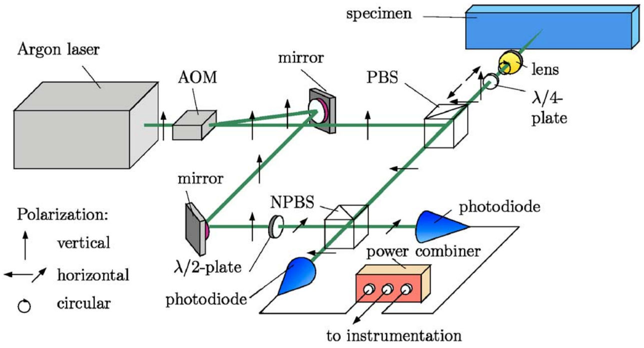

FIG. 1. (Color online) Schematic of the single-probe interferometer.

but allows horizontally polarized light to pass straight through. Consequently, the object beam is reflected 90°. The object beam then passes through a quarter-wave plate (λ/4 plate), at which point the beam becomes circularly polarized. The object beam then passes through a lens (microscope objective) that focuses the beam onto the surface of the object (specimen). The object beam then returns through the lens and the λ/4 plate, which causes the beam to become horizontally polarized. This horizontally polarized object beam then passes back through the PBS (this time unaffected) and continues into a nonpolarized beamsplitter (NPBS).

In contrast, the vertically polarized reference beam that leaves the AOM is reflected off two mirrors and passes through a half-wave plate (λ/2 plate), which changes the polarization from vertical to horizontal. This reference beam then passes through the NPBS, where it is recombined with the reflected object beam and focused onto two photodiodes. The signals of both photodiodes contain the same information and are combined with a power combiner in order to increase the carrier signal, and therefore the signal-to-noise ratio (SNR).

Now consider a dual-probe interferometer where the incident beam is separated into two different polarization directions, and each of these beams is used to build an individual probe. This design makes it possible to have the information of each of the individual probes contained in a single object beam without corrupting or interfering with each other. This dual-probe heterodyne interferometer (shown in Fig. 2) is similar to the single-probe version shown in Fig. 1, except that a λ/2 plate is now placed in front of the AOM, and this λ/2 plate is rotated such that the incident vertically polarized light is changed to 45° polarized light—a superposition of horizontally and vertically polarized light. By using the PBS as a filter, the vertically polarized beam is used as the object beam of the first probe, while the horizontally polarized beam (which passes through the PBS unchanged) becomes the object beam of the second probe. The reference beam of this system is also 45° polarized, and is recombined with the two (separately polarized) object beams (probe one horizontal, and probe two vertical) at the NPBS. The information of each object beam is combined with its (polarization appropriate) reference beam at the two photodiodes. Each photodiode in the dual-probe interferometer contains independent information from each of the single probes.

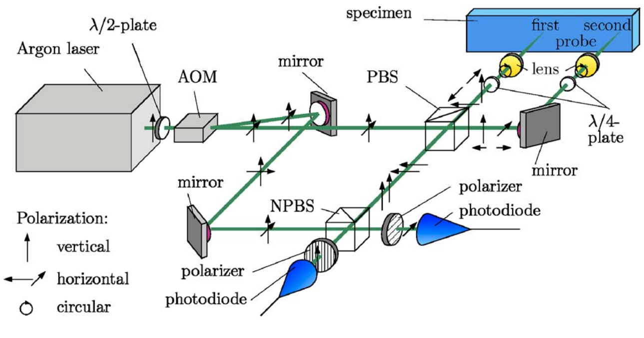

FIG. 2. (Color online) Schematic of the dual-probe interferometer.

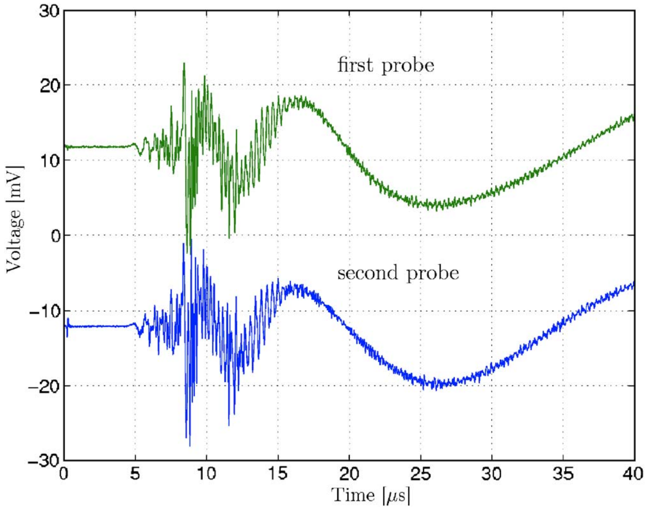

FIG. 3. (Color online) Lamb waves (independent and simultaneous) measured with the dual-probe interferometer.

Note that the (electrical) signal out of each photodiode is first bandpass filtered (40 MHz), and then passes through a 40 MHz frequency modulation (FM) discriminator. It is important to note that the modulation of the combined (object/reference) beam is equal to the frequency of the object beam, plus any Doppler shift due to the (out-of-plane) velocity of the point on the specimen's (object's) surface. The output signal from the FM discriminator is then lowpass filtered (10 MHz) and captured on a digital oscilloscope.

III. MEASUREMENT OF LAMB WAVES AND DISCUSSION

The robustness and accuracy of this dual-probe interferometer is demonstrated by simultaneously measuring the same Lamb wave at two different spatial locations, but with the same propagation distance. Broad bandwidth Lamb waves are generated with an Nd:YAG laser (4–6 ns pulse) (see Scruby and Drain[8] for details on the laser generation of Lamb waves). The laser detection of these Lamb waves is accomplished with the proposed dual-probe interferometer, measuring out-of-plane surface velocity (particle velocity) at two points on the specimen's surface. The specific specimen in this demonstration is a 1 mm thick, 3003 aluminum plate (300 × 300 mm), with the source-to-receiver distance the same for both probes, 26 mm (in opposite directions). Figure 3 shows the (transient) time-domain signals measured using the first and second probes, respectively. Note that the Nd:YAG laser fires at $t=0$ and generates the Lamb wave at the source location (the spot where the Nd:YAG hits the plate) and each Lamb wave signal represents an average of 30 Nd:YAG shots to increase SNR.

It is clear from Fig. 3 that this proposed dual-probe interferometer makes high-fidelity, point-like, independent (there is no bleed through from the first probe to the second probe, and vice-versa) measurements with a broad bandwidth (100 kHz to 10 MHz in this example). The independent and simultaneous measurements of this dual-probe interferometer are enabled by using the filtering properties of the PBS to separate 45° polarized light into two orthogonal polarization directions. The second advantage of this proposed interferometer is that because a common reference beam can be used, it only requires a few more optical components than a "standard" single-probe interferometer. Both of these attributes are advantageous for structural health monitoring applications, where the efficient, reliable, and accurate measurement of Lamb waves are of critical importance.

[1] R. Benz, M. Niethammer, S. Hurlebaus, and L. J. Jacobs, "Localization of notches with Lamb waves," J. Acoust. Soc. Am. **1114**, 677–685 (2003).

[2] D. Gardner, T. Hofler, S. Baker, R. Yarber, and S. Garrett, "A fiber optic interferometric seismometer," J. Lightwave Technol. **5**, 953–960 (1987).

[3] A. Lewin, "Optischer Aufbau von Polytec Vibrometern," in *4. Laser Vibrometer Seminar*, Polytec, Waldbronn, 1997, pp. 1–7.

[4] J. Huang and J. D. Achenbach, "Dual-probe laser interferometer," J. Acoust. Soc. Am. **90**, 1269–1274 (1991).

[5] A. D.W. McKie, J. W. Wagner, J. B. Spicer, and J. B. Deaton, Jr., "Dual-beam interferometer for the accurate determination of surface-wave velocity," Appl. Opt. **30**, 4034–4039 (1991).

[6] J. W. Littles, L. J. Jacobs, and A. H. Zurieck, "Single-sided ultrasonic technique to characterize thick FRP composites," J. Nondestruct. Eval. **17**, 223–230 (1998).

[7] D. Bruttomesso, L. J. Jacobs, and R. D. Costley, "Development of interferometer for acoustic emission testing," J. Eng. Mech. **119**, 2303–2316 (1993).

[8] C. B. Scruby and L. E. Drain, *Laser Ultrasonics: Techniques and Applications* (Adam Hilger, Philadelphia, 1990).