ELSEVIER

Journal of Neuroscience Methods 148 (2005) 122–129

JOURNAL OF NEUROSCIENCE METHODS

www.elsevier.com/locate/jneumeth

A self-mixing laser-diode interferometer for measuring basilar membrane vibrations without opening the cochlea

Andrei N. Lukashkin*, Mikhail E. Bashtanov, Ian J. Russell

School of Life Sciences, University of Sussex, Falmer, Brighton BN1 9QG, UK

Received 7 March 2005; received in revised form 14 April 2005; accepted 15 April 2005

Abstract

A laser-diode forms the basis of a displacement sensitive homodyne interferometer suitable for measurements from poorly reflective surfaces. The compact and cost-effective interferometer utilizes the self-mixing effect when laser light reflected from a moving target re-enters the laser cavity and causes phase dependent changes of the lasing intensity. A piezo positioner was used to displace the interferometer with known frequency and amplitude as a basis for real-time calibration of the interferometer's sensitivity. The signal-processing algorithm is described that allows measurements in presence of high amplitude noise leading to variation of the interferometer's operating point. Measurements of sound-induced basilar membrane displacements were made in the intact cochleae of rodents by focusing the laser beam of the interferometer through the transparent round window membrane. The interferometer provides a viable means for making subnanometre mechanical measurements from structures in the inner ears of small mammals, where opening of the cochlea is not practicable.

Keywords: Cochlear mechanics; Basilar membrane; Interferometry; Self-mixing

---

1. Introduction

Laser interferometry is now the standard technique for investigating the cochlea's mechanical responses. Both heterodyne (Willemin et al., 1988; Nuttall et al., 1991; Ruggero and Rich, 1991; Cooper, 1999) and homodyne (Khanna, 1986; Mammano and Ashmore, 1995; O'Neill and Bearden, 1995) gas laser systems have been developed and successfully used to advance our knowledge of sound-induced vibrations of structures in the mammalian cochlea. More recently, laser feedback or self-mixing interferometers have been applied in auditory research (Kössl and Russell, 1995; O'Neill and Bearden, 1995). In these interferometers, a coherent laser light, back reflected from a target, re-enters the laser cavity and interferes with the lasing field already present within the active zone. As a result of this interference the lasing power changes depending on the delay and on the phase of the back reflected light. These changes of the lasing power can be measured with the photodetector and used to make estimates of the target movement. The self-mixing effect is extremely sensitive to small amounts of back-reflection, which allows measurements to be made from poorly reflective surfaces. The estimates of Giuliani et al. (2002) show that the Fabry-Perot laser-diode (LD) used, for example, by Kössl and Russell (1995), produces a self-mixing signal measurable above the noise floor when only 10^{-12} of the emitted laser power re-enters the laser cavity. This characteristic makes it possible to use the LD interferometer for making measurements of the responses from the intact, unopened cochleae by focusing the laser beam through the transparent round window (Kössl and Russell, 1995; Legan et al., 2000). The opening of the cochlea is a critical stage in the preparation and frequently results in an elevation of hearing thresholds especially in small mammals. It also leads to changes in the cochlear hydrodynamic properties (Cooper and Rhode, 1996), which obscure the response of the intact cochlea.

A problem, intrinsic to homodyne interferometers is the dependence of their sensitivity, and hence their responses, on the operating point, e.g. on the working distance of the interferometer. It is possible to stabilize the operating point of the

---

* Corresponding author. Tel.: +44 1273 872802; fax: +44 1273 678433.
E-mail address: a.lukashkin@sussex.ac.uk (A.N. Lukashkin).

0165-0270/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jneumeth.2005.04.014

interferometer in its most sensitive position (Mammano and Ashmore, 1995; Murugasu and Russell, 1995) but another solution to this problem would be through the continuous monitoring of the interferometer sensitivity (e.g. see Roos et al., 1996). This paper describes a LD self-mixing interferometer where the second approach is taken. The interferometer was attached to a piezo actuator moving with known frequency and amplitude. The response of the interferometer at this frequency was used to calibrate continuously the interferometer sensitivity.

2. Methods

2.1. Interferometer design

A 10 mW, 670 nm wavelength LD package (APL670-10S, Access Pacific, UK) was mounted in a commercial collimation tube **L** (LT220P-B, Thorlabs Inc.) (Fig. 1A). The lens assembly consisted of a collimator (aspheric lens, NA = 0.25, C220TM-B, Thorlabs Inc.) and a focusing lens **F** (NA = 0.125, T45-234, Edmund Optics Ltd.). The laser beam could be focused into a spot of about 5 μm in diameter (measured at half-intensity level) at a distance of about 45 mm from the surface of the focusing lens. The only transparent region of operating laser-diode is the active zone of about 4 μm. Thus, the interferometer has a confocal arrangement to select reflected light only from the spot. The estimated depth of focus is about 20 μm for the numerical aperture (0.125) of the focusing lens. The lens assembly was firmly clamped in a mounting bar **C** that was screwed to the threads of a piezo flexure positioner **P** (P-280.10, Physik Instrumente). The piezo positioner was attached to a metal bar **B**, which was mounted in a micromanipulator. The resultant frequency-transfer characteristic (Fig. 1B) of the loaded piezo positioner was quite complex with the main resonance near 600 Hz. To measure the characteristic, the piezo positioner **P** was driven by sinusoidal voltages of different frequencies but of equal amplitude. Magnitudes and phase angles of the interferometer vibrations at different frequencies were measured using a similar interferometer. A light green filter attached to the mounting bar **C** was used as a target for the second interferometer to minimize reflections from back surface of the filter. The amplitude of piezo movements at low frequencies below the main resonance was calculated from the voltage-displacement sensitivity of 30 nm/V, according to the manufacturer's specifications. The manufacturer's specified sensitivity was confirmed by measuring the magnitude of the low-frequency voltage that was necessary to apply to the piezo **P** to observe the interferometric fringes, i.e. to move the interferometer by the strictly specified distance. The frequency-transfer characteristic was taken into account when assessing the amplitude and phase angle of the piezo's vibrations for a given value of sinusoidal input voltage at frequencies above the resonance.

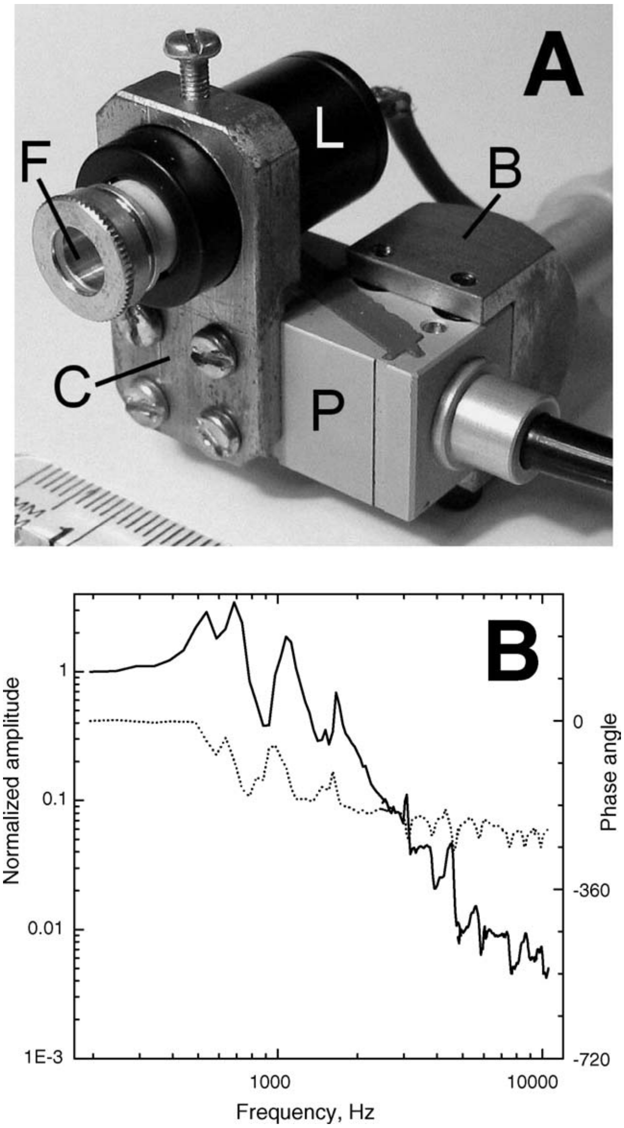

Fig. 1. General design of the laser-diode interferometer. (A) **L** indicates the lens assembly with the laser-diode mounted at the back of it and a focusing lens **F**. **C** is a metal clamping bar fixed to the piezo positioner **P**. Bar **B** is used to clamp the interferometer to a micromanipulator. A ruler with small divisions of 1 mm is shown in the bottom left corner of the figure. (B) Amplitude (solid line) and phase (dotted line) frequency responses of the piezo positioner with the interferometer attached. Amplitude response is normalized to the response at low frequencies.

2.2. Principle of operation for displacement measurements

In self-mixing or feedback interferometry a fraction of the laser light, reflected back from the target, re-enters the laser cavity and modulates the intensity of the lasing. These changes of the lasing intensity can be measured with a conventional photodetector and used to assess target movement. The realization of this sensing scheme is very simple when a LD is used. Modern LD packages include an integrated photodiode and no additional external photodetector is required. These essentially homodyne interferometers based on LDs