Self-mixing laser Doppler vibrometry with high optical sensitivity: application to real-time sound reproduction

Kazutaka Abe, Kenju Otsuka and Jing-Yuan Ko

1 Department of Human and Information Science, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan
2 Department of Physics, Tunghai University, 181 Taichung-kang Road, Section 3, Taichung 407, Taiwan
E-mail: ootsuka@keyaki.cc.u-tokai.ac.jp

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Abstract. Nanometre vibration measurement of an audio speaker and a highly sensitive sound reproduction experiment have been successfully demonstrated by a self-aligned optical feedback vibrometry technique using the self-mixing modulation effect in a laser-diode-pumped microchip solid-state laser. By applying nanometre vibrations to the speaker, which produced nearly inaudible music below 20 dB (200 µPa) sound pressure level, we could reproduce clear sound in real time by the use of a simple frequency modulated wave demodulation circuit with a −120 dB light-intensity feedback ratio.

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1. Introduction

Among the many applications of laser-diode-pumped solid-state lasers (DPSSLs), ultrahigh sensitivity response to external optical feedback light in the thin-slice microchip Fabry–Perot cavity configuration, resulting from the extremely short photon lifetimes compared to the population lifetimes [1], has led to self-aligned optical sensing applications, such as laser Doppler velocimetry [2]–[4], vibrometry [5] and imaging [6, 7]. The key idea is the efficient intensity modulation of microchip lasers through the interference between the lasing field and the coherent component of the frequency-shifted extremely weak scattered field fed back to the laser, in which the laser is modulated at the beat frequency between the two fields, where the modulation index is proportional to the fluorescence-to-photon lifetime ratio and the field–amplitude feedback ratio [6]. In contrast to traditional interferometry methods [8]–[10], the present technique utilizes a highly sensitive self-mixing modulation effect [1, 2] in microchip solid-state lasers. The high-sensitivity measurement can be done under the light-intensity feedback ratio below −100 dB without using highly sensitive electronics and sophisticated optical interferometers, in which the laser acts as a high-efficiency mixer oscillator and a shot-noise-limited quantum detector [11]. The distinctive feature of such a self-mixing scheme is that the sensitivity is determined only by the light intensity feedback ratio and the system performance does not depend on the laser output power. Most recently, we have demonstrated nanometre vibration measurement by using the self-mixing vibrometry scheme [12]. In this paper, we applied the self-mixing vibrometry scheme to a highly sensitive sound reproduction experiment and thus nearly inaudible music of 20 dB (200 µPa) sound pressure level (SPL) from a speaker connected to a compact disc (CD) player has been successfully reproduced in real time directly from nanometre-scale vibrations of the speaker by the use of a simple frequency-modulated (FM) receiver. Compared with the previous work [12], we increased the sensitivity by resonant enhancement of the carrier signal whose frequency was tuned to the vicinity of the relaxation oscillation frequency of the laser [3]. The main purpose of this paper is to demonstrate sound reproduction in the actual working system, in which we discuss the qualitative difference between the original music and the reproduced result.

2. Experimental apparatus

The experimental set-up is shown in figure 1. A 5 mm$^2$ c-plate Nd-direct compound LiNdP$_2$O$_{12}$ (LNP) laser with a 1 mm thick plane-parallel Fabry–Perot cavity was used. An end surface was coated to be transmissive at the laser diode (LD) pump wavelength of 808 nm (85% transmission) and highly reflective (99.9%) at the lasing wavelength of $\lambda = 1048$ nm. The other surface was coated to be 1% transmissive at the lasing wavelength. The collimated LD pump light was passed through anamorphic prism pairs (APP) to transform the elliptical beam into a circular one, and was focused on the LNP crystal by a microscope objective lens of $20 \times M$ magnification. The threshold pump power was 30 mW and the slope efficiency was 40%. A part (96%) of the output light was passed through a variable attenuator. The attenuated light was frequency-shifted by two acousto-optic modulators (AOMs) and was then impinged on a speaker having an Al-coated surface with an average roughness of 100 µm that was placed 90 cm from the laser. By changing the modulation frequencies of up-shift and down-shift AOMs (PbMoO$_4$; HOYA-SCHOTT A-150, 80 MHz central frequency) the optical carrier frequency was shifted by $f_c = 2$ MHz after a round trip for the feedback field. Another part (4%) of the output light was...
Figure 1. Experimental configuration for self-mixing laser Doppler vibrometry and real-time sound reproduction. LD: laser diode, APP: anamorphic prism pairs, OL: microscope objective lens, BS: glass-plate beam splitter, PD: photo-diode receiver, SA: rf spectrum analyser, VA: variable attenuator, AOM: acousto-optic modulators, DO: digital oscilloscope, FR: FM receiver, PC: computer.

Figure 2. (a) Modulated laser output waveform, (b) filtered waveform and (c) vibration waveform obtained by phase-sensitive detection with the Hilbert transformation. Modulation frequency: 22.6 kHz, applied voltage to the speaker: 2 V.

detected by an InGaAs photoreceiver (New Focus 1811: DC-125 MHz). The electric signal from the photoreceiver was delivered to a digital oscilloscope (Tektronix TDS 540D: DC-500 MHz) or an FM receiver consisted of an FM wave demodulation circuit and an amplifier. Depending on the measurement procedures, the receiver output was connected to a digital oscilloscope, a radio-frequency (rf) spectrum analyser (Tektronix 3026: DC-3 GHz) or another speaker.
3. Nanometre vibration measurement

First, let us briefly show vibration waveforms of the speaker we used. In this experiment, the carrier frequency shift $f_c$ was tuned to the vicinity of the relaxation oscillation frequency of the laser. Due to the resonant enhancement of the carrier signal at 2 MHz [3], the carrier-to-noise ratio (CNR) was increased up to 70 dB in the absence of vibrations, while CNR was 55 dB in the previous experiment without resonance enhancement [12]. A sinusoidal voltage from a signal generator was applied to the speaker instead of a CD player in figure 1. Figure 2 shows an example of modulated laser output waveforms and the corresponding vibration waveform. When the target (i.e. speaker) vibrates, the feedback field is FM and FM sidebands are created around the optical carrier frequency. Consequently, due to the self-mixing effect, the laser output intensity shows FM-waveform-type intensity variations whose carrier frequency is 2 MHz. Figure 2(a) shows the output intensity waveform which possesses higher harmonic components of the carrier frequency of 2 MHz due to a nonlinear response of the laser around the relaxation oscillation frequency, in which the FM modulation is too small to be identified in the figure. Figure 2(b) is the low-pass filtered waveform, in which higher frequency components are suppressed. The vibration amplitude in figure 2(c) was determined from the modulated laser output voltage shown in figure 2(b) by using the Hilbert transformation as reported in [12]. In short, from this transformation of time series, i.e. Gabor’s analytic signal, we calculated the analytic phase of the modulated signal by using LabView software on a PC and deduced the vibration amplitude $A_v(t)$ from the phase difference $\Delta \Phi(t)$ between the reference (carrier) signal and the modulated signal by using the relation $A_v(t) = \lambda \Delta \Phi(t)$. The analytic phase $\Phi_A$ is related to the analytic signal $V_A$ and its time average $\langle V_A \rangle$ by $V_A(t) - \langle V_A \rangle = R_A(t) \exp[i\Phi_A(t)]$. Here, $V_A(t) = I(t) + iI_H(t)$, where $I(t)$ is the time series of the scalar intensity and $I_H$ is its Hilbert transform.

Figure 3 shows output waveforms (voltage) from the FM receiver at different applied voltages to the speaker, where the vibration amplitudes were calibrated by using the result of figure 2. A super-heterodyne method with a central frequency of 10.7 MHz was employed for FM wave demodulation and the amplifier with 20 dB gain and 111 kHz 3 dB bandwidth was used. Note that the linearity of the loudspeaker we used was not good and the vibration amplitude was not proportional to the applied voltage, particularly in high frequency regimes. However,
the linearity of photodiode and FM receiver responses was ensured in the vibration frequency range up to 111 kHz. In the FM receiver circuit we used, higher harmonic components were suppressed and they have no effect on vibration waveforms. The demodulated output voltage, which is proportional to the vibration amplitude of the speaker (i.e. FM index $\beta = 2\pi A_v/\lambda$) was found to decrease with increasing the modulation frequency. In the whole experiment, the LNP laser output power was 2 mW and the light power impinged on the InGaAs detector was 80 $\mu$W. From the correspondence between the laser output waveforms and the numerical ones, which were obtained by simulations of the model laser with frequency-shifted feedback as reported in [11]–[13], the light-intensity feedback ratio was estimated to be $-100$ dB in the present experiment under the resonance enhancement condition. The minimum displacement which we could measure in the present system was $8 \times 10^{-2}$ nm at 20 kHz (i.e. minimum velocity of $10 \mu$m s$^{-1}$), while the maximum displacement was 0.8 mm at 20 Hz (i.e. maximum velocity of 10 cm s$^{-1}$). As for the higher frequency response, the frequency shift $f_c$ limits the measurement. In the lower frequency region, the residual environment vibration limits the measurable minimum displacement.

**Figure 4.** Dynamic power spectrum change of the laser output modulated by the music. Vertical axis: 10 dB/div, horizontal axis: 10 kHz/div, centre frequency: 2 MHz. Also see animation.
4. Real-time sound reproduction

Next, the signal generator was replaced by a CD player as shown in figure 1 and optical microphony experiments were carried out. In this sound reproduction experiment, we decreased the light intensity feedback ratio to $-120 \text{ dB}$ using the optical attenuator to eliminate the distortion of the carrier wave shown in figure 2(b), where CNR was decreased to 55 dB. A SPL was below 20 dB (200 $\mu$Pa) near the speaker 1 and the music from the CD player was nearly inaudible at a position 1 m from the speaker. In this situation, we connected the FM receiver output to another speaker 2 to reproduce the music. Let us show an example of the dynamic change of the power spectrum of modulated laser output in a short period of time with the music in figure 4. We can see the dynamic change of FM sidebands around the carrier frequency of 2 MHz. This is due to the fact that the laser is modulated by the interference between a lasing field and a FM scattered field from the speaker [11, 12]. An example of vibration waveforms in a short period of time, where the sound level abruptly changed, is shown in figure 5. It should be noted that the vibration amplitude is found to be as small as 50 nm in this case from the correspondence between the demodulator output voltage and the vibration amplitude in figure 3.

We have succeeded in reproducing the music clearly in real time from the speaker 2 which was connected to the FM receiver, as demonstrated in the movie (figure 6), in which the reproduced music and the corresponding dynamic power spectrum change are demonstrated. The recording was performed at a position 1 m from the speaker 2 with an electric pin microphone connected to a digital audio disc. The original music, which was collected by the pin microphone placed just in front of the speaker’s surface 1, is demonstrated in the movie (figure 7). It is apparent that the original music is clearly reproduced by probing nanometre-scale vibrations of the speaker’s surface with the self-mixing laser vibrometry scheme under the extremely weak light-intensity feedback ratio of $-120 \text{ dB}$. If one listens to the music carefully, however, the music reproduced purely from the nanometre vibration of the speaker 1 driven by the CD player differs slightly from the original. In short, lower-frequency sound components are pronounced as compared with the original sound, with the higher frequency component, especially around 3–6 kHz, being suppressed, as demonstrated in figures 6 and 7. (With increasing the voltage from the CD player, the higher frequency component was also clearly reproduced.) This results from the frequency-response characteristics of the speaker’s vibration amplitude (i.e. transfer function) used in the experiment, in which the demodulated output voltage that was applied to the speaker 2 was larger on the low frequency side and decreased as the sound frequency increased. On the other hand, the original music which was heard directly from the speaker 1...
reflects Fletcher’s frequency response of the human auditory system, with increased sensitivity in the frequency region around 3–6 kHz. In other terms, the speaker is designed taking the frequency response of the human auditory system into account. Finally, we use a sheet of paper vibrating by a sound wave as a target. Even in this case, the sound was reproduced in real time, in which the laser behaved as a high-sensitivity optical microphone.

Figure 6. Dynamics power spectrum change of the reproduced sound. Also see movie. Centre frequency: 10 kHz, 2 kHz/div. Vertical scale: 10 dB/div.
Figure 7. Dynamics power spectrum change of the original sound. Also see movie. Centre frequency: 10 kHz, 2 kHz/div. Vertical scale: 10 dB/div.

5. Conclusion

We have demonstrated highly sensitive sound reproduction with a laser-diode-pumped solid-state thin-slice laser in the self-mixing laser Doppler vibrometry scheme. Nearly inaudible music from a speaker below 20 dB (200 µPa) SPL has been clearly reproduced by the simple FM wave receiver under the light-intensity feedback ratio of −120 dB. The present technique may find medical and security applications such as real-time voice reproduction for throat-
disease patients in the presence of acoustic noise in the environment and voiceprint verification. The use of optical fibre access to the Adam’s apple or vocal chords would be effective. The long coherence length of solid-state lasers ($\geq 100$ m) may enable us to perform self-aligned fibre remote sensing of moving or vibrating targets located in places difficult to approach. The measurement of nanometre vibration amplitude under an extremely weak feedback ratio by the present technique would enable us to perform in situ analysis of moving or vibrating targets embedded in optically diffusive media in general.

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