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Demonstration of a Standing Light Wave with a Laser Pointer

Minsung Kim, Byoung Joo Kim, Hwan Hong Lim, Krishnamoorthy Pandiyan and Myoungsik Cha*
Department of Physics, Pusan National University, Busan 609-735

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Wiener's historic experiment on a standing light wave in 1890 introduced a representative example of the electromagnetic field superposition of light in modern textbooks on optics. In this research, we simply reproduce the experiment of Wiener for classroom demonstration. By using an inexpensive laser pointer as a light source and a weak diffuse reflection from slightly surface-scratched glass instead of photographic plates or fluorescent films, we demonstrate a standing light wave in real time. Furthermore, the coherence of the laser pointer can also be investigated in a simple experimental setup.

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I. INTRODUCTION

In 1887, Heinrich Hertz experimentally demonstrated that electromagnetic waves were consistent with Maxwell's theory, measuring their velocity, electric field intensity and polarization properties. He also produced standing radio waves by reflection from a zinc plate. Soon after Hertz's experiment, Otto Wiener performed a set of basic experiments on the nature of standing light waves [1]. He placed a very thin photographic emulsion inclined at a small angle to a silver mirror surface ($\sim 10^{-3}$ rad). A quasi-monochromatic light from a sodium arc lamp was incident normally on the mirror plane. After the emulsion had been developed, he found that it was blackened in equidistant parallel bands, which was due to the formation of nodes and antinodes of the standing light wave. With normal incidence and a slightly curved mirror pressed in contact with the emulsion, he was able to conclude that the fringes were due to the electric field vector alone. An excellent account of his experiment was introduced in textbooks on optics [2,3]. A few years after Wiener's experiment, a real-time observation method for a standing light wave was first reported by Drude and Nernst using an ultraviolet light source and a fluorescent thin film [4].

Recently, we reproduced the experiment of Drude and Nernst with improved efficiency by using a He-Ne laser and a highly fluorescent π -conjugated polymer thin film [5]. With the aid of modern technology, we were able to demonstrate real-time observation of standing light waves with extremely improved efficiency and simplicity. We also observed the standing wave using diffuse reflection from a slightly scratched glass plate instead of a fluorescent thin film. Compared to the fluorescent film method, the diffuse reflection method has the advantages of being a wavelength-independent observation and of having no optical damage problem.

In this article, we extend our scratched glass method by using a more accessible light source such as laser pointer, aiming at a demonstration in an undergraduate optics class or laboratory. In addition, we vary the distance between the mirror and the screen to analyze the coherence of the laser pointer by observing the contrast of the fringe pattern that occurs on the observation screen (glass plate). Our improved experiment can be easily implemented in undergraduate optics laboratories because of its simple and inexpensive optical setup.

II. THEORETICAL REVIEW

Standing waves are produced whenever two waves of an identical frequency travelling in opposite directions superpose with each other. Standing wave patterns are characterized by certain fixed points (or planes) where the fields undergo no displacement with time. These points of no displacement are called nodes. The nodes are always located at the same locations along the medium, giving the entire field pattern an appearance of standing still. Midway between every consecutive nodal point are points which undergo maximum displacement. These points are called antinodes. Antinodes are the points along the medium that oscillate the most.

Unlike traveling waves, standing waves transmit no energy. All the energy in the waves goes into sustaining the oscillations between the nodes, at which forward and re-

*E-mail: mcha@pusan.ac.kr; Fax: +82-51-515-2390

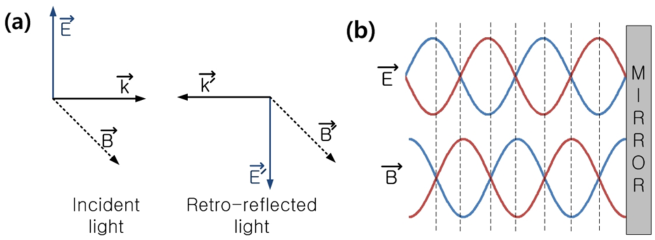

Fig. 1. (a) Wave vectors and fields for the incident and the retro-reflected light and (b) the corresponding electric field and magnetic field.

verse waves exactly cancel each other. If we assume an ideal situation in which no energy is lost on reflection, the electric fields of the forward- and the backward-travelling waves can be represented as

$$E_1 = E_0 \sin(kx + \omega t), \tag{1}$$

and

$$E_2 = E_0 \sin(kx - \omega t), \tag{2}$$

where E_0 is the electric field amplitude, k is the wave vector, x is the propagation direction, t is the time, and ω is the angular frequency. Here, we describe only the scalar components of the electric field for linearly polarized light. The resultant wave in the medium, by the principle of superposition, is

$$E(x,t) = 2E_0 \sin kx \cos \omega t. \tag{3}$$

This describes a wave that oscillates in time, but has a spatial dependence that is stationary: $\sin(kx)$. At $x = 0, \lambda/2, \lambda, 3\lambda/2 \ldots$, the amplitude is always zero (nodes) whereas at $x = \lambda/4, 3\lambda/4, 5\lambda/4 \ldots$, the amplitude is maximum (antinodes). The distance between two adjacent nodes or antinodes is $\lambda/2$.

The magnetic field can be calculated by using Faraday's law, resulting in

$$\overrightarrow{B}(x,t) = \frac{2\overrightarrow{E}_0}{c} \cos kx \sin \omega t. \tag{4}$$

Then, the nodes of the electric field correspond to the antinodes of the magnetic field, which make a fundamental difference from the travelling wave. The phenomenon can be explained as follow: In order to follow the right-hand rule ($\overrightarrow{k} \propto \overrightarrow{E} \times \overrightarrow{B}$), the direction of the magnetic field should be reversed if the electric field is unchanged, or the direction of the electric field should be reversed if the magnetic field is unchanged, as schematically depicted in Fig. 1. From Eqs. (3) and (4), we also note that when the electric field becomes zero, the magnetic field becomes maximum strong all the field energy. Thus, the field energy is exchanged between the electric and the magnetic fields, as in the case of the kinetic and the potential energies in mechanical standing waves.

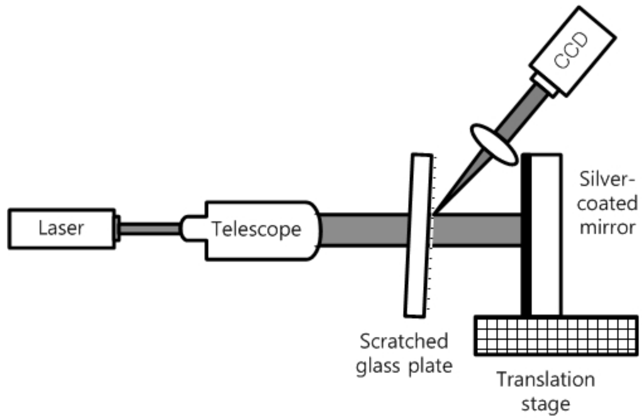

Fig. 2. Schematic diagram of the experimental setup.

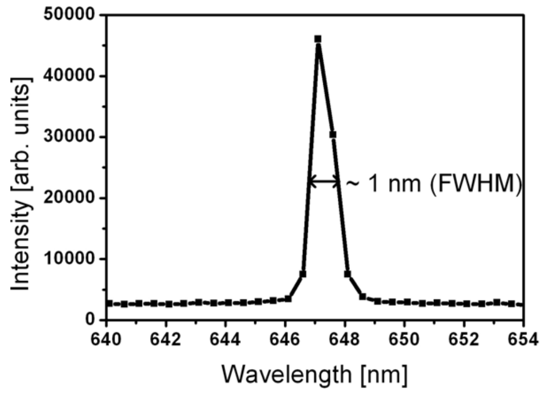

Fig. 3. Spectrum of the laser pointer.

III. EXPERIMENT

Our experimental setup diagram is shown in Fig. 2. We used a laser pointer as a light source [BOSS], which can be easily purchased at stationery stores. The laser beam was expanded to ∼10 mm in diameter, was collimated by using a telescope- lens combination to facilitate observation with the naked eye, and was incident normally on a highly reflecting plane silver mirror. To adjust the position of the mirror accurately and steadily, it was fixed in a precision translation stage/stepping motor system [THORLABS, T25X]. An anti-reflection-coated glass slide [Edmund-Optics, B270, MgF_2 coated] was used to visualize the standing waves. One side of the glass slide was gently rubbed with 1-μm (particle size) alumina powder to make uniform scratches. The glass slide produced weak scattering when a light beam was illuminated on the scratched surface.

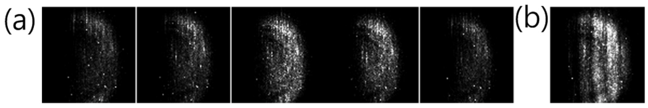

Fig. 4. Photograph of a scratched glass surface moved from one node to the next at normal incidence (a) and photograph of the fringe pattern when the glass slide was slightly tilted from normal incidence (b).

First, the spectral properties of the laser pointer were analyzed with a spectrometer (CVI, SM-240). The center wavelength and the full width at half maximum (FWHM) of the source were measured to be 647 nm and ~1.0 nm, respectively (Fig. 3), which was limited by the resolution of the spectrometer. By carful alignment of the silver mirror and the laser source, we made the incident and the reflected light beam overlap each other. The observation glass slide was kept close to the silver mirror at the beginning. To capture the image of the standing wave produced on the scratched glass plate, we used a CCD camera [Sony XC-75].

IV. RESULT AND DISCUSSION

The scratched glass plate was aligned parallel to the wave front (normal incidence), and the mirror was translated along the direction of the wave vector in steps of 50 nm by using the translation stage. Figure 4(a) shows a series of pictures taken during the translation between two adjacent nodes (distance of $\lambda/2$). From the photograph, it is evident that the brightness observed in the scratched glass plate represents the presence of antinodes. By moving the mirror, we could observe periodic changes in the intensity of the scattering pattern. Next, we slightly tilted the scratched glass slide, giving a small angle of incidence to visualize a few interference fringes on the glass plate. From Fig. 4(b), we can see the presence of nodes and antinodes due to the formation of a standing wave. The tilt angle was estimated to be approximately 10^{-4} rad. from the measured fringe spacing of about 3 mm.

Further, we estimated the coherence length of the light source by observing the fringe contrast by changing the distance between the mirror and the glass plate. Figure 5(a) shows the fringe pattern of a standing wave on the tilted glass screen by using a He-Ne Laser (λ = 543.5 nm). The fringe contrast was measured to be more than 40% up to 14 cm, from which one can evaluate the coherence length to be ~28 cm for the He-Ne laser. Figure 5(b) shows the fringe pattern of the laser pointer. We could clearly see the formation of nodes and antinodes up to 12 cm, after which the pattern was not prominent. Also, we observed that the standing wave pattern repeatedly appeared and disappeared within a 12 cm distance, which could be due to unstable mode-hopping of the laser pointer.

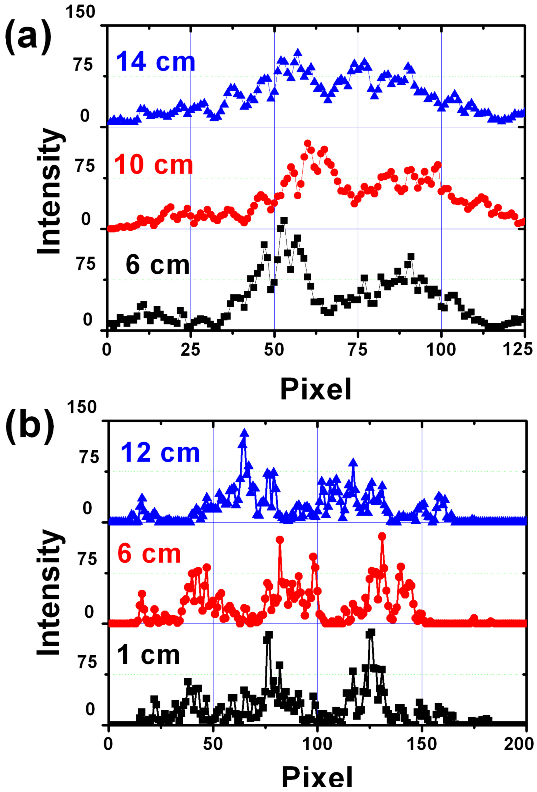

Fig. 5. Fringe pattern of a standing wave at three mirror-plate distances by using (a) a cw He-Ne laser (543.5 nm) and (b) laser pointer.

When we experimented with various laser pointers, the standing wave was not observable with all of them. This could be explained by the multimode operation or frequent mode-hoping in the diode laser source. In order to observe a standing wave, the laser needs to operate in a single mode for a reasonable time duration. (Mode-hopping within a narrow bandwidth would not be a problem.) Typically, the cavity length of a laser pointer is ~0.2 mm which gives a mode spacing of ~1 nm, corresponding to a coherence length of ~0.5 mm. If the spectral width of a laser pointer is less than 1 nm, the laser pointer can operate in a single mode. One can choose a proper laser pointer for the standing wave experiment by measuring either the spectral width or the coherence length as in our experiment. Here the fringes were observed up to 12 cm distance (24 cm round trip). As demonstrated in Fig. 5(b), we verified that the laser pointer was operating practically in a single mode when stabilized for a sufficient warm-up time. With such laser pointers, we did not observe frequent mode-hopping during the experiment. However, some laser pointers never showed standing waves, probably due to frequent mode-hopping in spite of a long warm-up time. This is understandable because cheap laser pointers lack precise control over the current and the temperature.

V. CONCLUSION

We reproduced Drude and Nernst's standing wave experiment by using a laser pointer as the light source and a scratched glass plate as the detecting screen. We also estimated the coherence length of the light source by calculating the fringe contrast of the nodes and the antinodes. This method has the advantages of being a wavelength-independent observation and of having a simple and low-cost optical setup. Therefore, this experiment can be easily implemented in an undergraduate optics laboratory for demonstration of a standing light wave and a coherence length measurement.

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