An optical interferometry experiment in the time-frequency domain

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ABSTRACT

We have developed an optical heterodyning experiment for the undergraduate physics laboratory curriculum that permits observation of optical beat phenomena associated with the interference of two light beams with slightly different frequencies. For optical beat frequencies below 10 Hz the interference of the light beams is observed on a viewing screen as a slowly drifting Michelson interference fringe pattern. For beat frequencies greater than 10 Hz the drift of the interference fringes is too rapid to be observed visually; however, if a photodetector is placed so as to detect light from within the rapidly drifting fringe pattern, the time variation of the detected light signal can be amplified and fed to a loudspeaker, allowing an individual student or a lecture audience to hear the beating of the two light beams. Since commercial amateur radio transceivers are used to control the frequencies of the two interfering light beams, the transceivers can be modulated with a voice signal to generate single sideband modulated light beams that can be demodulated using standard optical homodyne detection techniques. This simple optical communications system demonstrates clearly how transmitter and receiver design principles at radio frequencies can be transferred to optical frequencies for the implementation of modern lightwave communication systems.

1. INTRODUCTION

When the interference properties of light waves are demonstrated for lecture audiences or are investigated quantitatively in the undergraduate laboratory, it is most often by observing stationary patterns of constructive and destructive interference, such as those associated with a Michelson interferometer fringe pattern, a diffraction pattern produced by a grating, or a volume interference pattern stored permanently within a hologram. Such demonstrations are ordinarily analyzed in terms of the wavelength of the light beams, that is, in terms of the spatial periodicity of the light wave. The opportunities for producing time-varying optical interference patterns are much more limited; however, time-varying interference patterns can be observed in fringe counting applications such as the precise interferometric measurement of distances, the laser wavemeter, and measurements of the index of refraction of a gas cell placed in one arm of a Michelson interferometer. Even though these techniques involve time-varying interference patterns, the phenomena are typically analyzed in terms of the wavelength of the light beams.

We have developed an undergraduate laboratory experiment that demonstrates directly the temporal periodicity (frequency) of light waves and that complements the usual spatial interference demonstrations discussed in terms of the spatial periodicity of light waves. In the experiment, two laser beams that differ slightly in optical frequency are combined to produce an interference beat note with a frequency equal to the difference in optical frequency of the two laser beams. For sufficiently low beat frequencies the beating of the two laser beams is observed as a steadily drifting Michelson interference fringe pattern, and for beat frequencies in the range of audio frequencies a photodetector can convert electronically the light beating signal to produce an audible beat note that vividly demonstrates the temporal interference of the two light beams.

The analysis of the experiment can be carried out solely with reference to the frequencies of the laser beams present in the experiment. Student understanding of the experiment requires a careful appreciation of a group of frequencies that span fifteen orders of magnitude, including the optical frequency of the HeNe laser (474 THz), the frequency shift produced by the acousto-optic modulators (30 MHz), and the low frequency beat note (0-20 kHz). Understanding the optical beat signal is relatively easy as beat phenomena are familiar to student from other contexts. Students who have experience with

stringed musical instruments such as the guitar should be familiar with the tuning procedure that is used to adjust string tension by eliminating the beat note produced by the string and a tuning fork placed on the instrument soundboard In another context, perhaps more directly relevant to the experiment described here, students should be reminded of the presence of the some times annoying steady whistles that can be heard late at night while listening to the AM broadcast band or to shortwave broadcasting stations. These beat signals result from transmitting stations that broadcast on slightly different frequencies so that their carrier waves interfere to produce a steady beat note at a frequency given by the difference of the two transmitter carrier frequencies.

Commercial amateur radio transceivers are used in this experiment primarily to frequency shift the laser beams so that an adjustable and stable optical beat frequency is produced; however, the versatile modulation capabilities of these transceivers allow for a significant extension of the experiment beyond the production of a steady sinusoidal beat note between the two laser beams. With the equipment described here it is possible to configure an optical transmitter and optical homodyning receiver that demonstrates single-sideband (SSB) and frequency modulation (FM) optical communication techniques. This extension further emphasizes the role of heterodyning and homodyning at optical frequencies, as well as showing how communications principles developed for the radio frequency spectrum can be translated to optical frequencies where the much greater available bandwidth can be exploited for high speed optical communication systems.

2. EXPERIMENT

The optical configuration used in this experiment is shown in Fig. 1. The beam from a 1 mW helium-neon laser ($\lambda_0 = 633$ nm, $v_0 = 474$ THz) is split by beamsplitter BS1 to produce two beams that pass to Intra-Action ADM-40 acousto-optic modulators AOM1 and AOM2. The acoustic power to AOM1 and AOM2 is supplied by two commercial ICOM 745 amateur radio transceivers that provide approximately 5 W of radiofrequency power at frequencies f_1 and f_2 near 29.900 MHz. The 29.900 MHz operating frequency represents a compromise between the capabilities of the transceivers, which only operate to a maximum frequency of 29.950 MHz, and the limitations of the acousto-optic modulators,
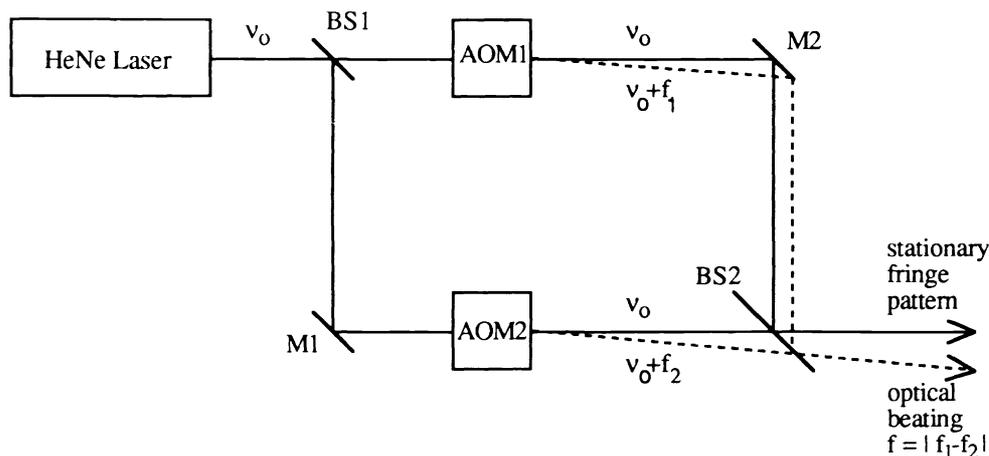

Fig. 1. Offset-homodyning configuration used in the present experiment. The undiffracted and diffracted (frequency up-shifted) beams are observed on a distant viewing screen. A photodetector (not shown) can be placed in the path of the combined, frequency-shifted beams to detect the optical beating signal electronically.

which are designed for optimum efficiency in the frequency range 30-50 MHz. The principal advantages of using the commercial transceivers are (a) their low cost compared to commercial frequency synthesizers, (b) their relatively good frequency stability compared to typical general purpose acousto-optic modulator drivers, and (c) the wide range of possible modulation modes, including continuous wave (CW), upper sideband (USB), lower sideband (LSB), and frequency modulation (FM).

The undiffracted beams from AOM1 and AOM2 at frequency v_0 are recombined at beamsplitter BS2 to produce a stationary interference fringe pattern on a distant viewing screen. The first order diffracted (frequency up-shifted) beams at frequencies v_0+f_1 and v_0+f_2 are also recombined at beamsplitter BS2, but only produce a stationary fringe pattern on the viewing screen when $f_1=f_2$. For $f_1 \neq f_2$ the diffracted beams interfere to produce optical beating at a frequency f given by $f = |f_1-f_2|$. Since these interfering beams are produced by frequency shifting light beams that are derived from the same laser, the beating phenomenon described here is termed optical offset-homodyning, as opposed to true optical heterodyning, where light beams from two independent lasers interfere to produce optical beating.

Once the apparatus has been aligned the following observations can be made.

(1) The fringe pattern produced by the diffracted beams at frequencies v_0+f_1 and v_0+f_2 can be seen on the viewing screen to be in a steady state of drift when the optical beat frequency f is less than 10 Hz. The radio transceivers have a frequency stability of better than 0.1 Hz per 10 s, so that it is easy to adjust their frequencies to maintain a steady drifting of the interference fringes over periods of more than a minute. When the transceivers are adjusted to produce beat frequencies that exceed 10 Hz the interference pattern drifts so rapidly that the fringes appear completely blurred to visual observation.

(2) For beat frequencies greater than 10 Hz, a photodetector can be placed within the rapidly drifting interference pattern so that the time variation of the light intensity can be detected electronically. When the output of the photodetector is amplified and fed to a loudspeaker, the movement of the interference fringes across the face of the photodetector can be heard as a steady audio tone at the beat frequency f. The output of the photodetector can also be viewed on an oscilloscope as shown in Fig. 2(a) or a spectrum analyzer as in Fig. 2(b).

It should be mentioned that direct radiofrequency energy from the two radio transceivers can be picked up and mixed inadvertently by the photodetector and associated electronics, leading to a spurious beat note that appears even if the laser beams are blocked. To avoid such an unwanted signal, it is necessary that all cables are well shielded and that the radio transceivers are placed well away from the
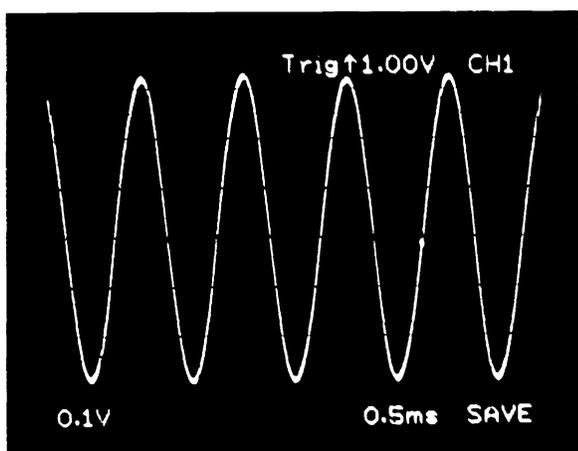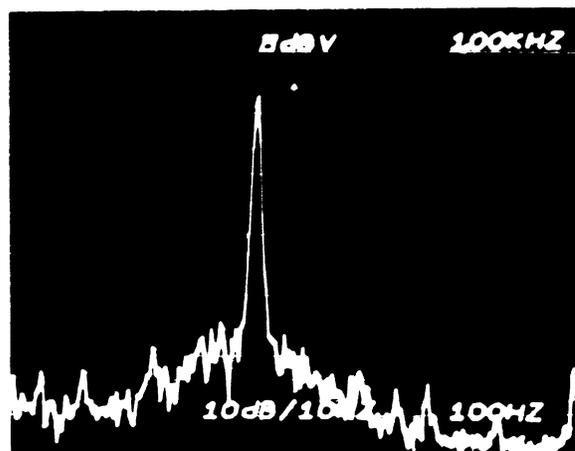
(a)   (b)

Fig. 2. (a) Oscilloscope (vertical: 0.1 V/cm, horizontal: 0.5 ms/cm) and (b) spectrum analyzer (vertical: 10 dB/cm, horizontal: 100 Hz/cm, trace center frequency: 1.00 kHz) traces for a beat frequency of 940 Hz.

photodetector electronics.

(3) The radio transceivers provide an opportunity to produce single-sideband (SSB) modulated light beams that can be demodulated using standard homodyning receiver methods.[1] For example, if the radio transceiver supplying f_1 is voice modulated in the USB mode by speaking into the transceiver microphone, then when f_2 is set to f_1 the beat frequencies detected at the photodetector contain the voice frequencies introduced by the transceiver at f_1. The quality of the detected USB voice signals is excellent and the tuning of f_2 near f_1 leads to the usual and somewhat amusing shift of voice frequencies that is characteristic of SSB signal reception in radio communications.

(4) Although the production of an FM communications system is not a part of our regular student experiment, it can easily be demonstrated in a slightly modified configuration of the present apparatus.[2] To operate in this mode, AOM1 is voice modulated at frequency f_1 using an ICOM 745 transceiver operating in the FM mode. AOM2 is not driven by a transceiver and therefore only an unshifted beam at v_0 emerges from it. The beamsplitter BS2 is adjusted to bring the FM modulated beam from AOM1 to combine with the unshifted beam at frequency v_0 from AOM2. The FM modulated beam at v_0+f_1 and the unshifted beam at v_0 interfere and mix in the photodetector to produce an FM modulated beat note at f_1 that can be fed to the antenna terminal of a radio transceiver (the one that is not modulating AOM2 in this mode) and can be detected as an FM signal by tuning the receiver to frequency f_1. Again, it is important to verify that the FM signal detected at f_1 is actually due to the interference and mixing of the two light beams, and is not due to leakage of radiofrequency signal from the transmitter operating at f_1 directly into the receiver electronics.

3. DISCUSSION

In our first year of experience with this experiment, twenty two students, individually or in pairs, completed all of the above measurements with little or no difficulty. When students enter the laboratory the apparatus is demonstrated, critical alignment problems are pointed out, and students make notes of unusual features of the apparatus. The instructor then asks the students to leave the room and the entire apparatus is dismantled into components. The students are then allowed to return to the laboratory to reassemble, align, and make measurements, all of which is usually accomplished in three to four hours.

At some point during the laboratory period it is useful to emphasize a few important points about the experiment. First, the optical beat note is audibly detected to be very stable, even though the HeNe laser that is used in the experiment is unstabilized and therefore the laser frequency v_0 shifts randomly by many MHz each second. It is important for students to realize that the offset-homodyning configuration (as opposed to true heterodyning requiring two independent laser sources) succeeds because only the difference between the two shifted frequencies is detected as a beat signal and is therefore independent of the HeNe laser frequency. Second, the SSB and FM voice signals placed on the light beam are in a sense encrypted by the random fluctuations of the HeNe laser frequency v_0 and that successful decryption of the voice signal requires interference and mixing with a second beam derived from the same laser. These considerations can lead to an interesting discussion of the security against unwanted interception of information transmitted by lightwave communication systems that use homodyne or offset-homodyne detection schemes, such as the one used in this experiment.

After each laboratory period, one of the transceivers is taken to our amateur radio station and put "on the air" to demonstrate the intended use of the transceivers in the 10 meter amateur radio band. This provides an opportunity to discuss further the reception and transmission of SSB signals and the origin of heterodyning schemes in standard radio practice. In this context, the optical experiment they have just performed represents a natural translation of standard radio techniques from radio frequencies near 30 MHz to light frequencies near 474 THz, a region of the electromagnetic spectrum nearly seven orders of magnitude higher in frequency.

4. REFERENCES

1. M. Ross, *Laser Receivers: Devices, Techniques, Systems*, John Wiley, New York, 1966.
2. J.E. Appleby, *Offset Homodyning: Applications in Lightwave Communications and Optical Spectroscopy*, B.A. thesis, Middlebury College, unpublished, 1991.