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TECHNICAL NOTE

Simple two-frequency laser

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The optics of a simple two-frequency laser is presented. It consists of a laser, a half-wave plate, and an electro-optic modulator. Because of a simple on-axis optical setup, it has high stability, easier operation, and high efficiency, without reducing the available coherence length of a laser and is suitable for two-frequency interferometry.

Keywords: *two-frequency laser; electro-optic modulator; two-frequency interferometry*

P. Dirksen et al.[1] proposed a novel two-frequency laser, in which there is a slight frequency difference between the linearly polarized components in two orthogonal planes. It consists of a laser, two Wollaston prisms, and two acousto-optic modulators (AOM). One Wollaston prism acts as a beam-splitter, and the other acts as a beam-combiner. The frequency shifts are attributable to the diffraction characteristics of an AOM under Bragg condition. Two AOMs are used for getting a moderate frequency difference for easy electric signal processing. Although it has some merits, as described in Dirksen's paper, there are some disadvantages in Dirksen's two-frequency laser.

1. It may reduce the available coherence length of a laser.
2. The efficiency will be decreased as the frequency difference is changed so that the Bragg condition is no longer satisfied.
3. The optical alignment is not easy because of the performances of Wallaston prisms and AOMs.

In commercial two-frequency interferometers, a Zeeman laser,[2] an acousto-optic modulator,[3,4] a rotating polarization component,[5] or a moving diffraction grating[6,7] is used for generating two beams with slightly different frequencies. For a Zeeman laser or an acousto-optic modulator, the difference frequency range is from several MHz to 100 MHz. The frequency is so high that it requires a special electronic signal-processing system. Hewlett Packard and Zygo have dedicated instruments for this purpose, which cost about $10,000 (U.S.). In some other designs, a rotating polarization component or a moving diffraction grating is used. Although its difference frequency range is within the operation range of an ordinary electronic signal-processing system, mechanical vibration may influence the stability of the optical structure; thereby decreasing measurement resolution, unless special care is taken about mechanical stability. In this paper, a simple two-frequency laser is presented. It consists of a laser, a half-wave plate, and an electro-optical modulator (EOM). Our method requires only an ordinary electronic signal-processing system and costs $200 (U.S.). In addition, because of a simple on-axis optical setup, it has high stability, easier operation, high efficiency, all without reducing the available coherence length of a laser.

The principle of operation is explained in *Figure 1.* For convenience the $+z$-axis is in the propagation direction, and the y-axis in the vertical direction. Let the light coming from a laser be linearly polarized. A half-wave plate H is set up to rotate this input polarization to a polarization direction that is at 45° to the x-axis. If the fast axis of the EOM under an applied electric field is at 0° to the x-axis, and the potential difference is V, then the phase retardation of the y-axis component relative to the x-axis component for either the transverse or longitudinal mode of electro-optical modulators is given by[8]

$$\Gamma = \frac{\pi V}{V_{\lambda/2}} + \Gamma_0 \tag{1}$$

where $V_{\lambda/2}$ is the half-wave voltage, and Γ_0 is the

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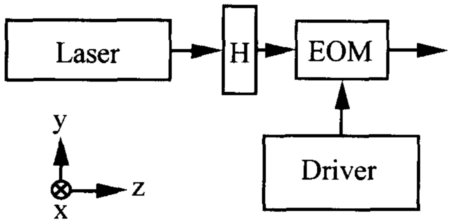

Figure 1 Block diagram of the simple two-frequency laser; *H,* half-wave plate; EOM, electro-optic modulator

phase retardation without external electric field. If V is a sawtooth voltage signal with a period T with DC bias voltage V_b, as shown in *Figure 2,* then V is a function of time t and can be expressed as follows:

$$V(t) = V_b \pm \left(\frac{t}{T} - m\right) \cdot 2V_{\lambda/2}, \quad \text{at} \quad mT \leq t \leq (m+1)T \tag{2}$$

where $m = 0,1,2,3,\ldots$, and the positive part means the waveform shown in *Figure 2a,* the negative part in *Figure 2b.* So we have

$$\Gamma = \pm 2\pi\left(\frac{t}{T} - m\right) + \phi_0 = \pm 2\pi(ft - m) + \phi_0, \quad \text{at} \quad mT \leq t \leq (m+1)T \tag{3}$$

where f is the frequency of the sawtooth voltage signal, and ϕ_0 is the initial phase retardation and can be zero with a moderate choice of V_b. Consequently, the light amplitude after passing through the EOM is given by

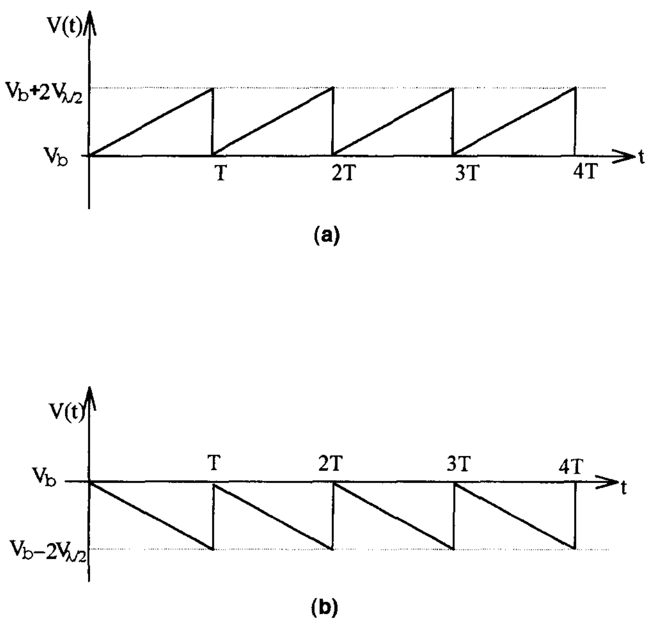

Figure 2 Two possible sawtooth voltage signals that are applied to an electro-optic modulator

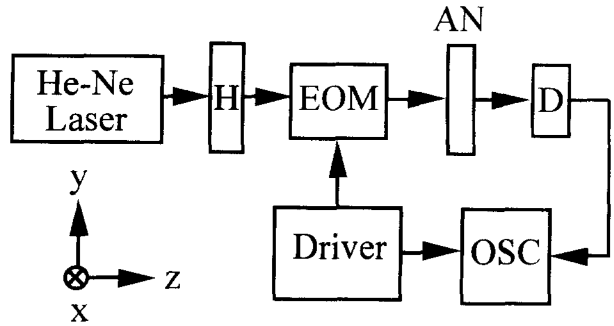

Figure 3 Experimental setup for demonstrating the proformance of the simple two-frequency laser; *H,* half-wave plate; EOM, electro-optic modulator; AN, analyzer; D, photodetector; OSC, oscilloscope.

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} E_0 \exp(i2\pi f_0 t) \\ E_0 \exp[i(2\pi(f_0 \mp f)t - \phi_0)] \end{pmatrix} \tag{4}$$

where f_0 is the optical frequency. From Equation (4), it is obvious that the y-component has a frequency shift with an amount of $\mp f$.

To show the performance of this simple two-frequency laser, an analyzer AN with its transmission axis at 45° to the x-axis is located behind the EOM, as shown in *Figure 3,* to extract the necessary polarization components to interfere. For easier observation, the driving sawtooth voltage signal and the signal detected at the detector D were monitored by an oscilloscope. A He–Ne laser with a 632.8-nm wavelength and an electro-optic modulator (PC 200/2), manufactured by Electro-Optics Developments Ltd. with a half-wave voltage 170V, were used in this experiment. The results are shown in *Figure 4.* The upper part represents the driving sawtooth voltage signal, which is applied to an electro-optic modulator with a frequency 2 kHz.

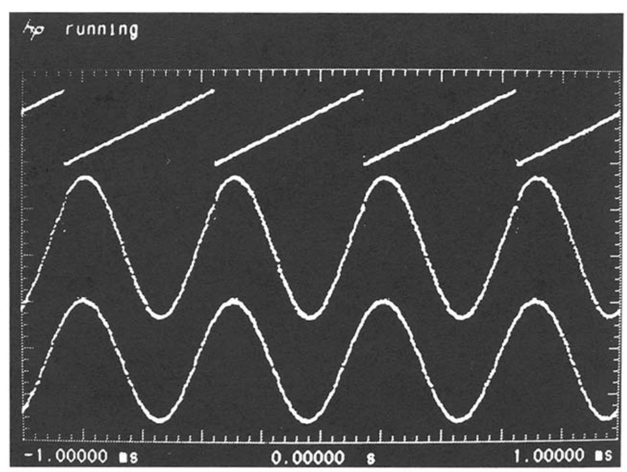

Figure 4 Recorded signals shown in an oscilloscope: upper trace, sawtooth voltage signal applied to the EOM; middle trace, the interference signal; lower trace, the interference signal after bandpass filtering.

The middle part represents the waveform of the signal detected at the detector. The detected signal is guided into a bandpass filter to filter out its spike, and it becomes a clean sine waveform, as shown in the lower part. All parts in *Figure 4* have the same frequency. The shift frequency is not so high as that produced by an acousto-optic modulator, a Zeeman laser, or a tunable laser diode, and it is in the range of $10^2 \sim 10^5$ Hz. Thus, it is very easy for electric signal processing.

A simple two-frequency laser is presented in this technical note. It has been used for measuring small displacements[9] as well as phase retardation[10] of a wave plate. Besides these applications, it has many merits, such as high stability, easier operation, and high efficiency, without reducing the available coherence length of a laser, and it is very suitable for two-frequency interferometry.[11–13] If a laser diode is used, it makes this simple two-frequency laser more compact. Moreover, it has a wider tunable frequency range, and the range depends on the characteristics of the EOM and the driving frequency to the EOM.

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