Cavity tuning characteristics of orthogonally polarized dual-frequency He-Ne laser at 1.15 μm

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The cavity tuning characteristics of orthogonally polarized dual-frequency He-Ne laser at 1.15 μm are presented. Vectorial-extension model based on semi-classical laser theory reveals that cavity tuning characteristics are related to beat frequency, relative excitation, and type of Ne isotope. Distortions of cavity tuning curves become moderate with the increase of beat frequency because of the weakening of the cross-saturation effect. Distortions are enhanced with the increase of relative excitation because of the combined action of the self-saturation and cross-saturation effects. By adopting dual-isotope Ne instead of monoisotopic Ne, distortions are reduced because of the misalignment between peaks of the self-saturation and net gain coefficients. The theoretical calculations are in good agreement with the corresponding experimental results.

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Intracavity laser method is widely used in precision measurement because numerous characteristics of laser are sensitive to changes in intracavity. These characteristics include spectrum[1,2], wavelength[3,4], beat frequency[5], and intensity[6,7]. Intracavity laser spectroscopy is one of its most important applications. It is sensitive, fast, selective, and capable of analyzing gases, liquids, plasmas, and heterogeneous media. The optical losses in the near infrared region are less than those in the visible region, and a wide spectral range is often required to record a considerable number of absorption or gain lines simultaneously. Hence, infrared and tunable lasers are chosen for intracavity laser spectroscopy. These types of lasers have been used in the detection of biological structure, molecular spectrum, and trace elements[8,9].

Intracavity tuning displacement sensing (ITDS) is based on the intensity characteristics of an orthogonally polarized dual-frequency He-Ne laser. By inserting birefringent elements into the laser cavity, one laser frequency splits into orthogonally polarized dual frequencies. The intensities of these frequencies will change when the cavity mirror moves, which is repeated at every longitudinal mode interval. Moving direction is judged by the sequence of appearance of the two frequencies, whereas the magnitude of the displacement is calculated according to the shape of the cavity tuning curves after signal processing[7]. The ITDS method has several merits including the capability for self-calibration of every half wavelength, non-requirement for a frequency stabilization system, and a simple structure. As regards the application of ITDS method, stability and measuring range are prime considerations. The limitations in the gain of He-Ne laser at 0.63 μm could cause the laser to stop outputting when the loss exceeds the gain in the intracavity. Moreover, detuning of the laser cavity may occur because of the vibrations in the cavity mirror. Compared with the He-Ne laser at 0.63 μm, the He-Ne laser laser at 1.15 μm is more suitable for the ITDS method because of its higher active medium gain value. This leads to relatively higher output power, better stability of laser cavity, and longer measuring range.

Cavity tuning curves are the foundation of the ITDS method and numerous other methods. After mastering the laws, suitable parameters of the laser could be selected to achieve the given requirement after calculation. In this letter, the vectorial-extension model based on the semi-classical theory is developed to explain the cavity tuning phenomena of orthogonally polarized dual-frequency laser. It reveals that the most related parameters are beat frequency, type of Ne isotope, and relative excitation. The cavity tuning mechanism of He-Ne laser at 1.15 μm is discussed in detail. Experiments are conducted to prove the theoretical predictions.

According to the semi-classical theory[10,11], the intensities of the orthogonally polarized dual-frequency He-Ne laser can be described by the differential equation:

$$\dot{I}_{1/2} = 2I_{1/2}\left(\alpha_{1/2} - \beta_{1/2}I_{1/2} - \theta_{12/21}I_{2/1}\right). \quad (1)$$

When crystals are used to create frequency splitting, two frequencies can be named o-light and e-light, separately. In this case, 1/2 means 1 for o-light and 2 for e-light, I_1 and I_2 are the separate intensities of o-light and e-light in an arbitrary unit, α is linear net gain coefficient, β is the self-saturation coefficient, and θ is cross-saturation coefficient.

The two-mode steady-state solution of Eq. (1) is given by

$$I_{1/2} = \frac{\alpha_{1/2}\beta_{2/1} - \alpha_{2/1}\theta_{12/21}}{\beta_1\beta_2 - \theta_{12}\theta_{21}}. \quad (2)$$

Equation (2) is complicated because the expressions of α, β, and θ are not linked directly to the change of cavity length x. Multilevel variables and functions are defined between them and analytic solutions are not established. However, Eq. (2) can be used in full for numerical analysis of detailed data of laser and evaluation of efficiency of the solution. Intermediate variables and functions are well described by Lamb *et al.*[10,11].

In order to take into account the collisions of atoms which are neglected in the semi-classical theory, intermediate coefficients are extended vectorially[12]. The average attenuation constants of the energy levels are replaced by the half-width of homogeneous broadening and thus, all complex denominators $D(\nu)$ in expressions of coefficients should be changed as

$$\mathrm{D}(\nu)=\frac{1}{\gamma+\mathrm{i}\nu}\quad\longrightarrow\quad \mathrm{D}(\nu)=\frac{\exp(\mathrm{i}s)}{\gamma+\mathrm{i}\nu},\tag{3}$$

where ν is the frequency, γ is half-width of homogeneous broadening, and s is proportional to the He^3 pressure in the He-Ne laser. In particular, an intermediate variable that should be explained is the relative excitation η, which is given by

$$\eta=\overline{N}/\,\overline{N}_{\mathrm{T}},\tag{4}$$

where $\overline{N}$ is the average atomic population inversion and $\overline{N}_{\mathrm{T}}$ is the atomic population inversion on the threshold where the laser frequency is tuned to the peak of the atomic resonance curve. η is assumed to be equal between sublevels when we focus on the intensity characteristic. Three important factors related to the cavity tuning curves are found. These are beat frequency, type of Ne isotope, and relative excitation.

Cavity tuning curves of monoisotoplic Ne^{20} with various beat frequencies are presented in Fig. 1. Cavity tuning curves are given as a function of the change of cavity length when the beat frequency $d\nu$ is equal to 100, 200, and 375 MHz. The change in cavity length can be caused by the axial displacement of a cavity mirror. Parameters used in calculations are as follows. The cavity length is 200 mm, transmissivity of the output mirror is 2.5%, and reflectivity of the other mirror is 99.9%. The pressure is 500 Pa and He^3:Ne^{20} is equal to 9:1. Relative excitation used in the calculation is 1.6.

The longitudinal mode interval Δ is given by

$$\Delta=c/2L,\tag{5}$$

where c is the speed of light and L is the cavity length. The longitudinal mode interval is equal to 750 MHz at L=200 mm. In this case, the beat frequency of 375 MHz is half of the longitudinal mode interval and the frequencies of laser are evenly spaced. Furthermore, it should be noted that when the split frequency of the next longitudinal mode appears in the lasing bandwidth, the beat frequency changes to the longitudinal mode interval without the initial frequency difference. The two operating frequencies that come from different longitudinal modes under this circumstance and their relative magnitude changes account for this observation.

As shown in Fig. 1(a), relative intensities of o-light and e-light change twice near the position of x=0. With the growth of beat frequency, the distortions in the cavity tuning curves become moderate as shown in Fig. 1(b). When the beat frequency is equal to half of the longitudinal mode interval, a change in the direct intensity, instead of distortions, occurs between two frequencies as shown in Fig. 1(c).

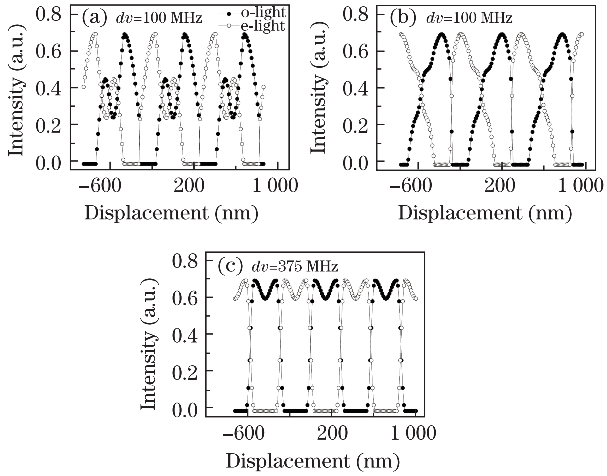

Fig. 1. Calculations of cavity tuning curves of monoisotoplic Ne^{20} with different beat frequencies.

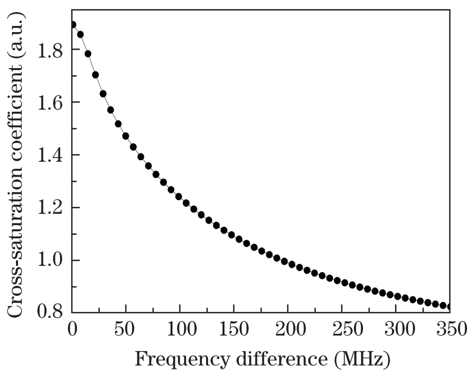

Fig. 2. Change of cross-saturation coefficient with respect to change in beat frequency.

The distortions of cavity tuning curves are caused mainly by the cross-saturation effect. The self-saturation effect leads to a dip in the cavity tuning curve of each frequency, whereas the cross-saturation effect leads to a mutual disturbance of two frequencies. Figure 2 depicts the change in cross-saturation coefficient with respect to the change in beat frequency at $x=0$. This position is the symmetric center of all these coefficients, where $\theta_1=\theta_2$.

Figure 2 shows that the cross-saturation coefficient decreases rapidly with the increase in beat frequency. The weakening of the cross-saturation effect is the main reason why distortions of cavity tuning curves become moderate with the increase of beat frequency.

Dual-isotope Ne with Ne^{20}:Ne^{22} =1:1 is widely used in order to avoid the Lamb dip. After changing the monoisotoplic Ne^{20} to dual-isotope Ne with Ne^{20}:Ne^{22} =1:1 and holding other parameters constant in contrast to Fig. 1(a), the cavity tuning curves of dual-isotope Ne with Ne^{20}:Ne^{22} =1:1 are obtained and presented in Fig. 3. It shows that distortions of cavity tuning curves disappear at $d\nu$=100 MHz. The reason lies in the relationship between the linear net gain and self-saturation coefficient. The frequency interval between central frequency of Ne^{20} and Ne^{22} is 261 MHz[13], which results in two peaks and a dip in the curve of

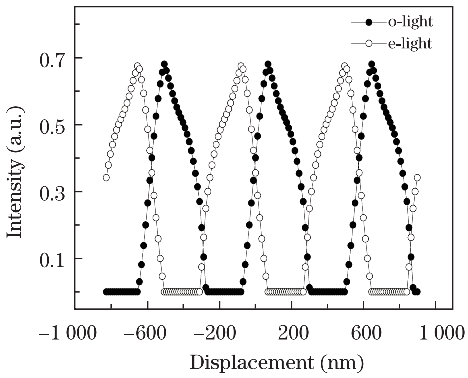

Fig. 3. Calculation of cavity tuning curves of dual-isotope Ne at $d\nu = 100$ MHz.

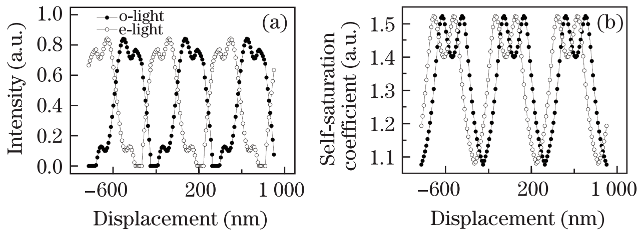

Fig. 4. Calculations of self-saturation coefficient of dual-isotope Ne at $\eta = 2.0$.

self-saturation coefficient. The dip is at the center of the curve of the self-saturation coefficient where the linear net gain coefficient achieves the maximum value. Hence, self-saturation effect is not strong enough to cause a dip in the cavity tuning curve.

Relative excitation represents the level of atomic population inversion. η is positively related to gain and negatively related to cavity loss and $\eta = 1.0$ is the critical point of laser output. After enlarging the relative excitation to $\eta = 2.0$ and holding other parameters constant in contrast to Fig. 3, cavity tuning curves are derived and depicted in Fig. 4.

Figure 4(a) shows that the distortions of cavity tuning curves reappear when relative excitation increases. On the other hand, Fig. 4(b) shows the corresponding self-saturation coefficient. Numerical calculation results indicate that distortions of cavity tuning curves are the combined action of the self-saturation and cross-saturation effects. The dip of the cavity tuning curve and the peak of self-saturation coefficient are in the same position, and a dip in one frequency leads to a peak in the other frequency because of the cross-saturation effect.

The schematic structure of experimental setup is shown in Fig. 5. The operating wavelength of He-Ne laser is 1.15 μm. A concave output mirror M1, a plane reflective mirror M2, and a He-Ne laser discharge tube T compose the half-extra cavity laser. The window plate with anti-reflection coating on both surfaces is denoted as W, whereas Q is a quartz plate placed obliquely to maintain a certain angle between the crystal and laser axis. Because of the birefringence effect, two laser cavities in physics are created when the crystal axis is not parallel to the axis of laser cavity. Through this way, one laser frequency splits into two frequencies, which are polarized orthogonally with a certain beat frequency decided by the angle between the axes of the crystal and of the laser cavity. The two frequencies are named o-light and e-light based on the concept of crystal optics. On the other hand, piezoelectric transition (PZT) is a piezoelectric ceramic on which M2 is mounted. The elongation of PZT is nearly linear to the supply voltage. When M2 moves along the laser axis, the frequencies go through the gain curve with a specific beat frequency, forming two cavity tuning curves. The polarizing beam splitter (PBS) is a Wollaston prism used to separate the orthogonally polarized dual frequencies. D1 and D2 are two photoelectrical detectors used to detect the output intensities of two lights. The two frequencies which are the output of M1, are separated by PBS and subsequently projected on D1 and D2.

The length of the capillary is 70 mm, the diameter is 1.3 mm, and the cavity length is 200 mm. Transmissivity of M1 is 2.5% and the radius of curvature is 1 m. High reflective coating (> 99.9 %) on the left surface of M2 is presented. The pressure is 500 Pa and He^3:Ne^{20} is equal to 9:1. In order to avoid the Lamb dip in the cavity tuning curves, He^3:Ne^{20}:Ne^{22} should be equal to 9: 0.5: 0.5 when the dual-isotope Ne is used. The discharge current is 3 mA. The anti-reflection and high reflective coatings are located at the central wavelength of 1.15 μm.

The experiment on the orthogonally polarized dual-frequency He-Ne laser at 1.15 μm is implemented. A scanning interferometer is used to detect the longitudinal mode of each light, which is linearly polarized and perpendicular to each other. The beat frequency is detected by photoelectric receiver and measured by frequency counter using the polaroid, which is oriented 45° to the polarization directions. The beat frequency can be adjusted by rotating the crystal. Figure 6 demonstrates the cavity tuning curves of monoisotoplic Ne^{20} with various beat frequencies of 100, 200, and 375 MHz. Figure 7

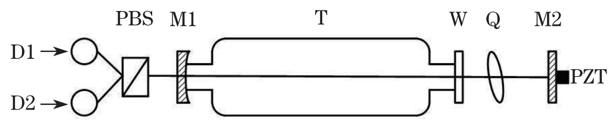

Fig. 5. Schematic structure of experimental setup.

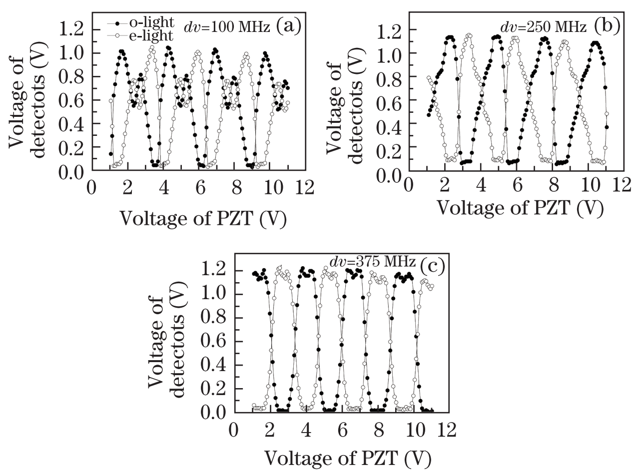

Fig. 6. Experiment on cavity tuning curves of monoisotoplic Ne^{20} with different beat frequencies.

demonstrates the cavity tuning curves of dual-isotope Ne with a beat frequency of 100 MHz. By enlarging the length of the capillary to 120 mm, which indicates an increase in relative excitation, and holding other parameters constant in contrast to Fig. 7, the cavity tuning curves are obtained as shown in Fig. 8.

The theoretical calculations are in good agreement with the corresponding experimental results, which offer support for further application of the intracavity laser method. In the case of ITDS method, suitable cavity tuning curves should be adopted to observe the displacement conveniently and correctly. Thus, the corresponding parameters could be selected from the theory model.

In Fig. 7, dual-isotope Ne is used with He^3:Ne^{20}:Ne^{22} that is equal to 9:0.5:0.5, beat frequency of 100 MHz, and a length of capillary of 70 mm. The PZT is driven by a triangular supply voltage, causing the cavity length to change forward and backward. The sequence of o-light and e-light is opposite to that of PZT moving in a

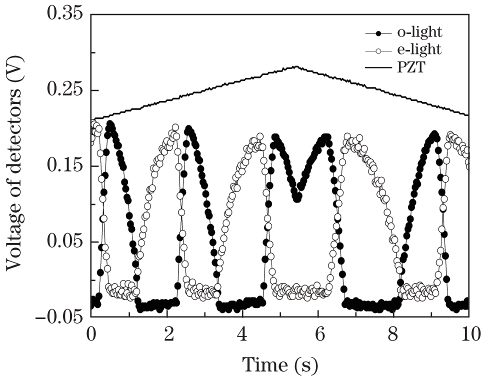

Fig. 7. Experiment on cavity tuning curves of dual-isotope Ne at $d\nu = 100$ MHz.

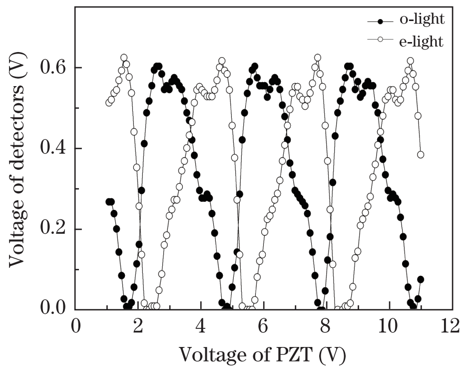

Fig. 8. Experiment on cavity tuning curves with dual-isotope Ne when the length of capillary is extended to 120 mm.

different direction. These phenomena offer the method for direction judgment. The retardation between o-light and e-light is controlled by the beat frequency, which makes subdivision possible. If the requirement of application changes, the corresponding parameters can be selected easily using the theory model.

In conclusion, cavity tuning phenomena and the mechanism of orthogonally polarized dual-frequency He–Ne laser at 1.15 μm are presented. The vectorial-extension model based on the semi-classical laser theory is established in order to take into account the collisions of atoms. The model reveals that cavity tuning phenomena vary with beat frequencies, relative excitation, and type of Ne isotope. With the increase in beat frequency, distortions of cavity tuning curves become moderate because of the weakening of the cross-saturation effect. Distortions are reduced by the use of the dual-isotope Ne because of the misalignment between peaks of self-saturation and net gain coefficients. Distortions are caused by the increase in relative excitation because of combined action of self-saturation and cross-saturation effects. The theoretical calculations are in good agreement with the corresponding experimental results. The research results offer support for further application of the intracavity laser method.

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