行政院國家科學委員會專題研究計畫成果報告

子計畫三：THz 訊號產生用高功率雙波長雷射及其應用之研究

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一、中文摘要

本計畫展示雙波長外腔雷射所產生的 *THz* 訊號的頻率穩定與雙波長追蹤的特性。利用時間閘距穩頻技術，我們將 802.5*nm* 與 804.5*nm* 雙波長的頻率漂移量降為 86*kHz*，而兩波長所產生的 0.9*THz* 拍頻訊號的頻率漂移量更低至 17*kHz*。在雙波長之間的波長差從 0.2*nm* 調到 4*nm* 的調變範圍內，我們都可因雙波長追蹤特性，得到較穩定的 *THz* 拍頻訊號。

關鍵詞：雙波長外腔雷射、頻率追蹤、時間閘距穩頻技術、*THz*

Abstract

We show a unique dual-wavelength external-cavity laser (2-λ-*ECL*) with frequency tracking capability and obtain a stable beat frequency between the dual-wavelength output. By using a Fabry-Perot interferometer as the frequency discriminator and the time-gating technique in a servo loop, the peak-to-peak frequency fluctuations were stabilized, with respect to the Fabry-Perot cavity, to 86*kHz* in the dual-wavelength output at 802.5*nm* and 804.5*nm*, and to 17*kHz* in their 0.9*THz* beat signal. Similar performance was achieved for tuning of the dual wavelength separation ranging from 0.2*nm* to 4*nm*.

Keywords: Dual-Wavelength External-Cavity Laser (2-λ-*ECL*), Frequency Tracking, Time-Gating Technique, *THz*

二、緣由與目的 **INTRODUCTION**

Tunable external cavity semiconductor lasers (*ECL*)[1] are important for an array of applications such as wavelength-division-multiplexed (*WDM*) optical communication, high-resolution spectroscopy and optical metrology. Frequency control of such lasers is often mandatory in practice.[2] On the other hand, an *ECL* capable of generating multiple wavelengths is also desirable. An example of such lasers is the tunable continuous wave dual-wavelength external-cavity laser (2-λ-*ECL*) as we demonstrated earlier.[3,4] The coaxial output of the two modes of the 2-λ-*ECL* produces an intensity-modulated signal at frequencies tunable beyond 7*THz*.[5] This characteristics is ideal for applications such as the generation of terahertz signal by optical heterodyne conversion or photomixing,[6-8] for which the two laser modes should be frequency-locked and stabilized. We have demonstrated stabilization of the output of a 2-λ-*ECL* by locking one of the laser mode to a passive reference cavity.[9] A peak-to-peak frequency fluctuation of 4.2*MHz* corresponding to an Allan variation of 1.14×10^{-8} was achieved. It is, however, not possible to determine whether the two modes fluctuates in frequency independently or in unison. In this report, we show for the first time simultaneous frequency-tracking and stabilization of a tunable 2-λ-*ECL*.

三、結果 **RESULTS**

For frequency stabilization of the laser, we employed the time-gating technique[10] previously reported for a set of laser diodes. The basic principle is illustrated in Fig. 1. A triangular waveform voltage was used to scan the Fabry-Perot interferometer at a scanning rate of 400-*Hz*, as shown in Fig. 1(a). The amplitude of the scanning waveform was adjusted such that half of the scanning period T/T covers one free spectral range ν_{FSR} of the Fabry-Perot interferometer. This allowed the two laser frequencies ν_1 and ν_2 to appear twice within each period. Two pairs of time-gating band-pass-filter pulses are used to capture two separate laser frequency signals ν_1 and ν_2, as shown in Fig. 1(b) and (c). Although the bandwith of the Fabry-Perot interferometer is about 90*MHz*, only the peaks of the signals were captured, and the duration between the peaks was determined from the center zeros of their first derivatives with respect to time. Therefore, the duration was relatively accurate and independent of the Fabry-Perot linewidth. In practice, the duration τ_1 between the peaks of the two gated ν_1 signals was then converted into a voltage signal $V_1 = k\tau_1$, where k is a constant. Similarly, the duration τ_2 between the two gated ν_2 signals was converted into V_2. Consequently, for any fluctuations in laser frequency ν_1 and ν_2, the voltage signal V_i will vary according to $\Delta\nu_i = (\Delta V_i/k)\cdot(\nu_{FSR}/T)$, where $\Delta\nu_i$ and ΔV_i are the fluctuations in ν_i and V_i, respectively, for i = 1 and 2. We also measure a third voltage signal $V_{21} = k\tau_{21}$, which is for the measurement of fluctuations in the difference frequency $\nu_{21} = \nu_2 - \nu_1$ according to the relationship $\Delta\nu_{21} = (\Delta V_{21}/k)\cdot(2\nu_{FSR}/T)$. Here τ_{21} is the duration between the gated signals ν_1 and ν_2 within the same half-periods, as shown in Fig. 1(d). Either V_1 or V_2 was then sent into a Proportional-Integral-Differential (PID) controller. The output of the PID controller is used to drive a piezo-electric transducer (PZT) mounted on the *V*-shaped mirror for laser frequency stabilization of one cavity mode.

The frequency tracking capability and stability of the laser modes was obtained by converting the three fluctuating voltage signals ΔV_1, ΔV_2 and ΔV_{21} into $\Delta\nu_1$, $\Delta\nu_2$ and $\Delta\nu_{21}$ as given above. It should be noted that all the frequency fluctuations thus measured were referenced with respect to the Fabry-Perot interferometer, which is reasonably stable during the measurement period. Hence, the measured frequency stabilities of ν_1, ν_2 and ν_{21} are relative frequency stabilities. Figure 3 shows the converted $\Delta\nu_1$, $\Delta\nu_2$, and $\Delta\nu_{21}$ as a function of time during a 200-*sec* scan with a sampling interval of 0.5*sec*. As can be seen from the results, the two fluctuation signals $\Delta\nu_1$ of $\lambda_1 = 80444nm$ and $\Delta\nu_2$ of $\lambda_2 = 802\,44nm$ were nearly the same, with a peak-to-peak fluctuations of $\Delta\nu_{max} = 2\,MHz$, indicating fairly good tracking of two oscillating wavelengths. The square root of the Allan variances[11] for the two modes is $\langle\Delta\nu_1\rangle \cong \langle\Delta\nu_2\rangle = 8z\,kHz$, corresponding to a relative frequency stability of $\langle\Delta\nu_1\rangle/\nu_1 \cong \langle\Delta\nu_2\rangle/\nu_2 = 2\,40 \times 0\,0^{-10}$. As for the beat signal at $\nu_{21} = 0.93THz$, the fluctuation is relatively small. The square root of the Allan variances of ν_{21} is $\langle\Delta\nu_{21}\rangle = 0\,0\,kHz$. In addition, we also measured $\langle\Delta\nu_{21}\rangle$ at a fixed total output power as a function of the separation of the two wavelengths for a tuning range of $0.2nm \le (\Delta\lambda = \lambda_1 - \lambda_2) \le 4nm$, as shown in Figure 4. It can be seen that $\langle\Delta\nu_{21}\rangle = (17.2 \pm 0.4)kHz$, which is nearly independent of the separation between the two wavelengths within the above tuning range.

四、討論 DISCUSSION

The frequency tracking and stabilization of the dual-wavelength laser are realized because the two laser modes are coaxial. Consider two cavity-modes coaxial all over the cavity. The oscillating frequencies of the two cavity modes can be expressed by $\nu_1 = pLc/1L$ and $\nu_2 = qLc/1L$, where p and q are the two integers determined by the position of the *V*-shaped end mirror, c is the speed of light in vacuum, and L is the overall optical-path-lengths of the folded external cavity. Differentiating ν_1 and ν_2 with respect to L gives

$$\frac{\Delta\nu_1}{\nu_1} = \frac{\Delta\nu_2}{\nu_2} = \frac{\Delta\nu_2 - \Delta\nu_1}{(\nu_2 - \nu_1)} = -\frac{\Delta L}{L} \quad .(1)$$

As L varies, ν_1 and ν_2 follow up in phase. The shift $\Delta\nu_{21}$ of their beat frequency $\nu_{21} = \nu_2 - \nu_1$ is then subtractive: $\Delta\nu_{21} = \Delta\nu_2 - \Delta\nu_1$. Substituting this into Eqn. (1), we have, for $\nu_1 \cong \nu_2 >> \nu_{21}$,

$$\frac{\Delta\nu_1}{\Delta\nu_2} = \frac{\nu_1}{\nu_2} \cong 2 \quad (2)$$

and

$$\frac{\Delta\nu_{21}}{\Delta\nu_1} = \frac{\nu_{21}}{\nu_1} << 2\,. \quad (3)$$

Eqn. (2) suggests the feasibility of the frequency tracking of two laser cavity modes in our dual-wavelength laser. Eqn. (3) predicts that the beat frequency signal can be more stable than either cavity mode.

On the other hand, in the case of conventional heterodyne conversion involving two independent laser cavities, the fluctuations of ν_1 and ν_2 are random. The variation of the corresponding beat frequency becomes statistically additive: $\Delta\nu_{21}^2 = \Delta\nu_2^2 + \Delta\nu_1^2$. In other words, the beat signal of two independent lasers is less stable than that of a single 2-*λ*-*ECL*.

For a perfect tracking condition of two oscillating modes, we would expect $\Delta\nu_{21}$ be very small. However, our data shows $\Delta\nu_{21} > (\Delta\nu_2 - \Delta\nu_1)$, which suggests a slight effect of partially laser cavity dependent of the two oscillating modes ν_1 and ν_2. This may be attributed to the fact that the two coaxial modes are not perfectly coaxial within the entire cavity. In fact, the two modes do separate apart from each other within a relatively short distance between the lens and the *V*-shaped end mirror. Denoting L_1 and L_2 as the overall optical-path-lengths of the cavities for the two modes separately, we have $\Delta\nu_1/\nu_1 = -\Delta L_1/L_1$ and $\Delta\nu_2/\nu_2 = -\Delta L_2/L_2$. Assuming that ΔL_1 and ΔL_2 fluctuate simultaneously, we may set $\Delta L_1 = \beta\Delta L_2$, where β is a constant. For $\nu_1 \cong \nu_2$, $L_1 \cong L_2$, and $\Delta\nu_{21} \cong \Delta\nu_2 - \Delta\nu_1$ in this work, we obtain $\Delta\nu_{21} = (1-\beta)\Delta\nu_2$. Substituting 17*kHz* for $\Delta\nu_{21}$, 86*kHz* for $\Delta\nu_2$, 3.74×10^{14} *Hz* for ν_2, and 75*cm* for L_2 into the above expressions yields $\beta = 0.8$, $\Delta L_2 = -1.7\mathring{A}$, and $\Delta L_1 = -1.4\mathring{A}$, indicating a difference of $\Delta L_1 - \Delta L_2 = 0.3\mathring{A}$ in cavity length variation. This is reasonable since the *V*-shaped end mirror was mounted on a moving PZT. The random fluctuations in the cavity lengths due to environmental vibration noise can be considered as the major factor in preventing the perfect frequency tracking between the two modes in the duel-wavelength laser. Furthermore, since the frequency instability induced by the cavity length fluctuation is frequency independent, this is in qualitative agreement with the plot of $\Delta\nu_{21}$ as seen in Fig. 4. Although the extrinsic vibration noise can be dramatically improved with a frequency stabilization servo loop, we note that the frequency-tracking property is intrinsic for our laser configuration whether the laser is actively stabilized or not. Stabilization merely reduces the magnitudes of $\Delta\nu_1$, $\Delta\nu_2$, and $\Delta\nu_{21}$ as a whole.

五、計畫成果自評 SUMMARY

In summary, we demonstrated the tracking capability and relative frequency stability of two coaxial oscillating modes in a dual-wavelength external-cavity laser using a time gating technique and a Fabry-Perot interferometer as the frequency discriminator. When the laser was stabilized against a reference Fabry-Perot interferometer, the peak-to-peak fluctuations of the laser frequencies were able to be stabilized to 86*kHz* in the dual-wavelength output at 802.5*nm* and 804.5*nm*, and to 17*kHz* in their 0.9*THz* beat frequency signal. The frequency tracking operation results in a factor of five improvement in the relative frequency stability for the beat signal. Since the frequency tracking is a unique feature of the 2-*λ-ECL*, it should be an ideal light source for applications such as heterodyning or photomixing for the generation of tunable terahertz radiation. This work was supported in part by various grants of the National Science Council of the Republic of China.

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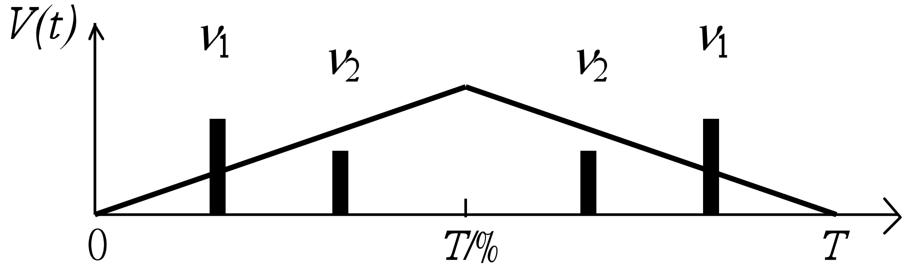
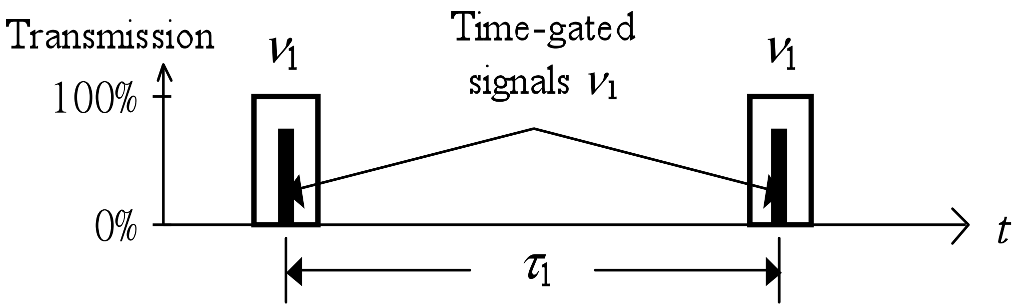
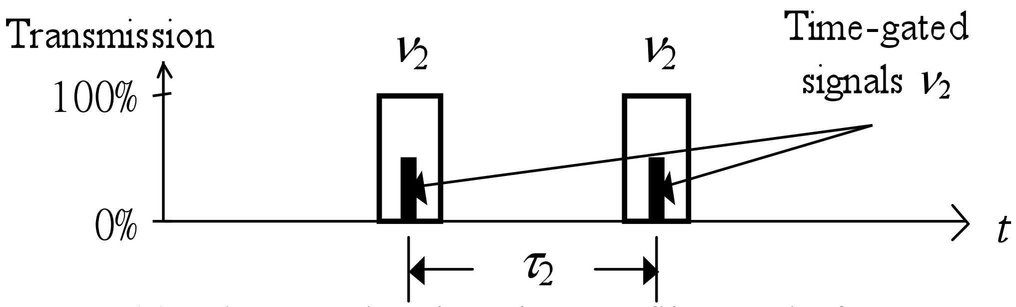


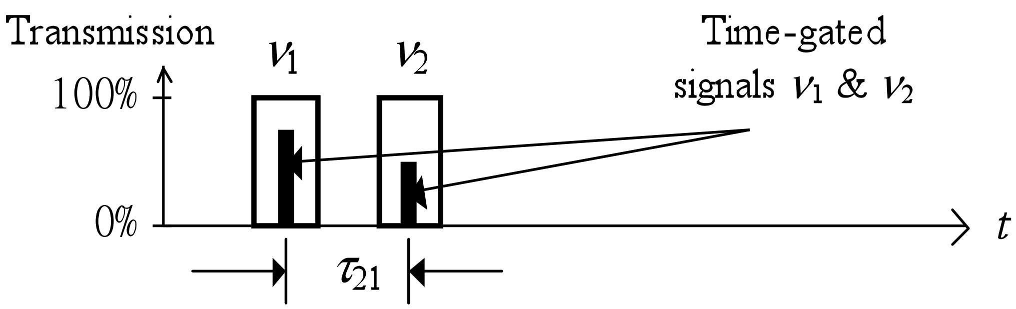
(a) Scanning waveform and two laser-mode signals



(b) Time-gating band-pass-filter pair for τ_1



(c) Time-gating band-pass-filter pair for τ_2



(d) Time-gating band-pass-filter pair for τ_{21}

Figure 1 Operating principle of time-gating technique.

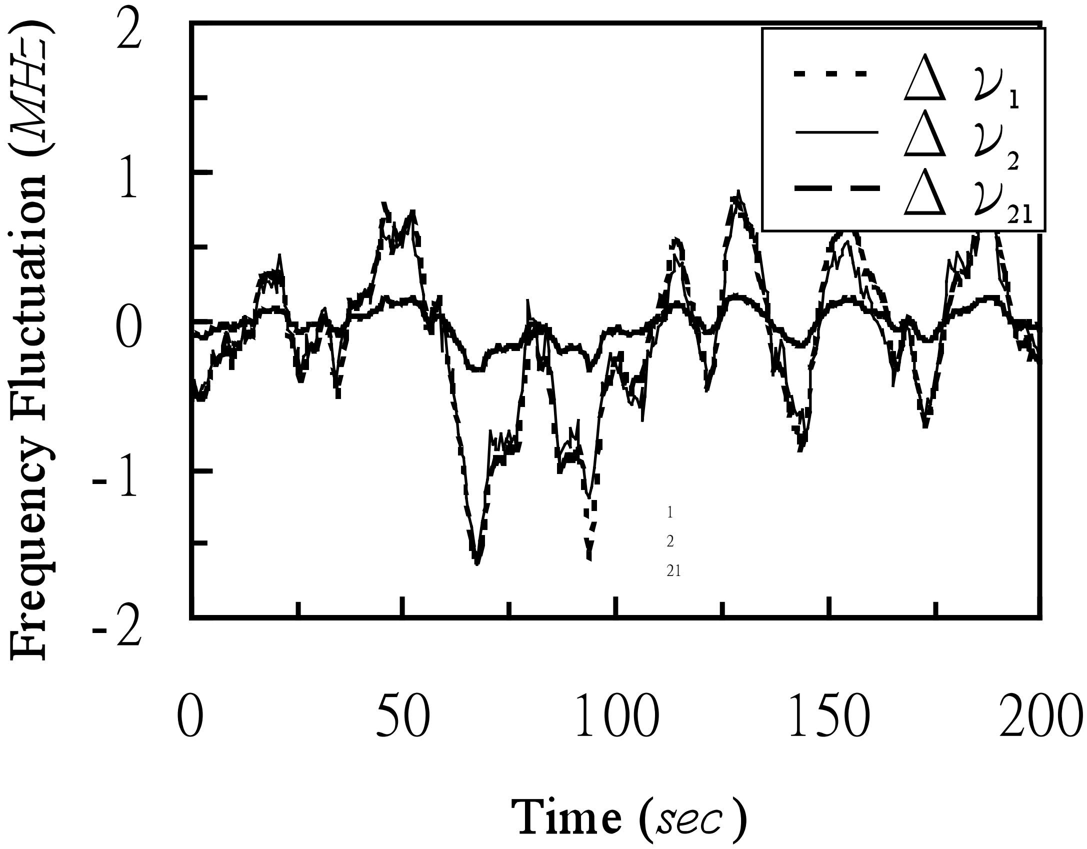


Figure 2. *Relative* **frequency fluctuations as a function of time for** $\Delta\nu_1$**,** $\Delta\nu_2$**, and** $\Delta\nu_{21}$**.**

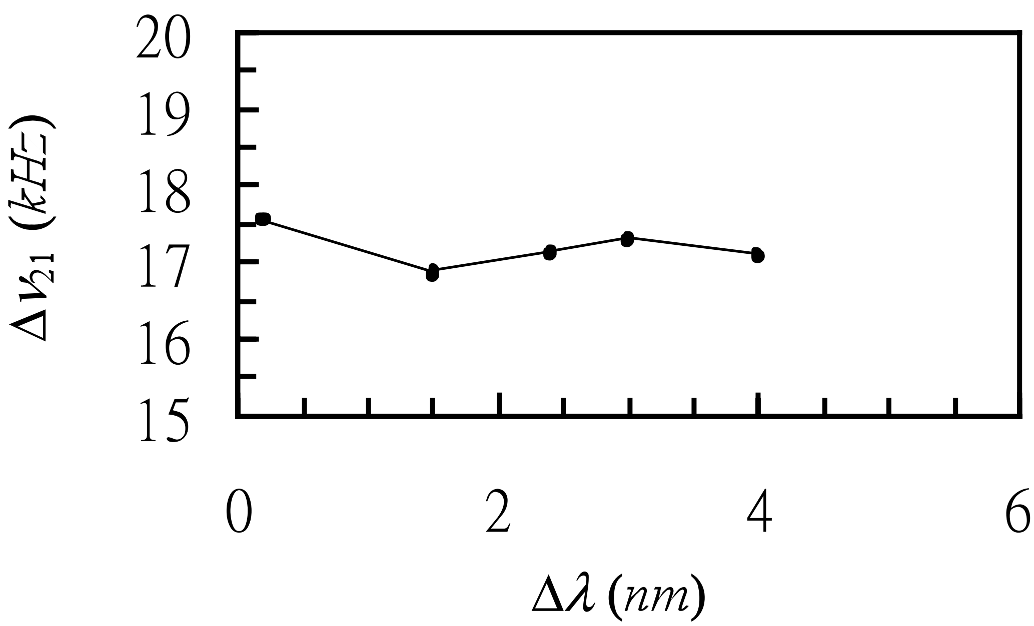


Figure 3. **Relative frequency fluctuations $\Delta\nu_{21}$ as a function of $\Delta\lambda = \lambda_1 - \lambda_2$.**