# Tunable and frequency-stabilized $CO_2$ waveguide laser

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**Abstract.** The optogalvanic effect (OGE) of $CO_2$ waveguide lasers and $CO_2$ lasers stabilized by the OGE and tuned by the compound cavity are investigated. The laser operates at 60 emission lines and the maximum single line power is 8 W. The stability of the laser in long-term operation is better than 0.8%.  [DOI: 10.1117/1.1518033]

Subject terms: frequency stabilization; optogalvanic effect; compound cavity tuning.

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## 1 Introduction

A study of a $CO_2$ laser stabilized by the optogalvanic effect (OGE) and tuned by the compound cavity is presented in detail in this paper. According to our study, we find that it can achieve not only a continuous tuning using the grating compound cavity, but also a stabilized frequency and power using the OGE of $CO_2$ waveguide lasers. The combination of these two points is an effective way to develop a new type of $CO_2$ waveguide lasers with stabilized frequency, good tunability, and other favorable functions.

This study shows that the amplitude, sensitivity, frequency response, and SNR of a $CO_2$ molecule increase dramatically with the enhancement of working air pressure. The later mathematical expression formula induced through the rate equation of the $CO_2$ laser level confirms our experimental results as well.

Combining our previous study of $CO_2$ waveguide lasers with a grating compound cavity,[1] we set up a tunable and frequency-stabilized $CO_2$ waveguide laser system. The compacted structure and the continuously tunable frequency and power are the most obvious advantages for a compound cavity. The largest single line power is 8 W and the output of 60 emission lines are obtained with the change of the coupling efficiency of a coupling cavity and the incidence angle of a compound cavity grating. In the processes of frequency stabilization and branch selection, which are controlled by an advanced computer center, a long-term power stability better than 0.8% and a frequency stability around $10^{-9}$ were obtained.

## 2 OGE of $CO_2$ Waveguide Lasers

### 2.1 *Expression of the Optogalvanic Currents*

Based on the operation of a $CO_2$ molecule laser,[2–4] the mathematical expression formulas of the optogalvanic signal total response $S(t)$ and amplitude $R(\omega)$ can be as the following, which are induced by the rate equation of the $CO_2$ molecule laser level:

$$S(t)=S_{01}[1-\exp(-t/\tau_{1A})]-S_{02}[1-\exp(-t/\tau_{2A})], \quad (1)$$

$$R(\omega)=\frac{S_{01}\tau_{1A}^{-1}}{\omega^2+\tau_{1A}^{-2}}-\frac{S_{02}\tau_{2A}^{-1}}{\omega^2+\tau_{2A}^{-2}}. \quad (2)$$

Assuming $\omega_c$ as the roll-back point of the frequency modulation, i.e., $R(\omega_c)=0$, we have

$$\omega_c=(S_{01}/S_{02})^{1/2}/(\tau_{1A}/\tau_{2A})^{1/2}. \quad (3)$$

In Eqs. (2) and (3), $S_{01}$ and $S_{02}$ are the high-frequency response part and the low-frequency response part of the optogalvanic signal, respectively; $\tau_{2A}$ and $\tau_{1A}$ are the relaxation times of the upper level and lower level of the $CO_2$ molecules, respectively; $t$ is the system light field function time; and $\omega$ is the light field modulating frequency.

### 2.2 *Experimental Measurement for the Optogalvanic Signals of $CO_2$ Waveguide Lasers*

Figure 1 is the experimental setup of a $CO_2$ waveguide laser stabilized by OGE and tuned by a grating compound cavity. The waveguide tube is 30 cm long; the tube diameter is 3 mm; the ratio of the mixed gases $CO_2$, $N_2$, He, and Xe is 4:3:16:1, and the air pressure varies from 20 to 100 Torr. For the each air pressure, the working current can vary from 2 to 15 mA and the truncated frequency is between 20 and 2000 Hz.

#### 2.2.1 *Relationship of optogalvanic signals and the working pressure and the modulating frequency*

Figures 2 and 3 represent the relationship of optogalvanic signals and the working pressure and the modulating frequency. Our study shows that $\omega_c$ shifts toward a higher frequency with an increase of the working air pressure be-

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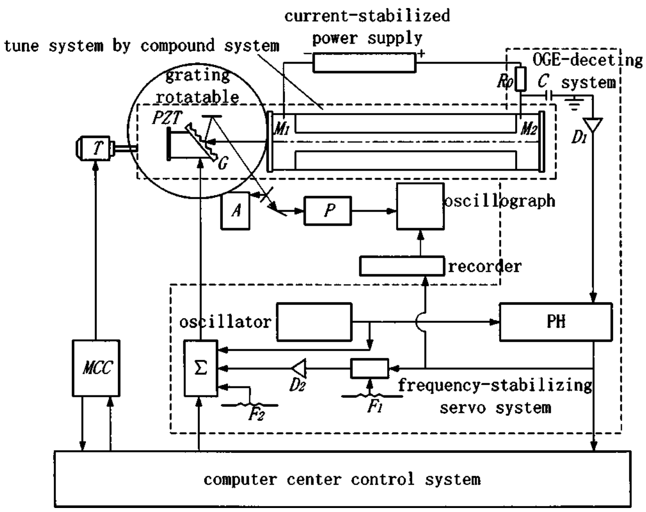


**Fig. 1** Experimental setup of a $CO_2$ waveguide laser stabilized by OGE and tuned by a grating compound cavity: $R_0C$; OGE-detecting network; $D_1$, frequency-selection preamplifier; $D_2$, voltage change and power amplifier; $F_1$, differential compensation amplifier; $F_2$, bias rectifier; Σ, sign integration; PH, phase-detecting and synchronous integrating circuit; $T$, stepper motor; MCC: control circuit of stepper motor; $A$, $CO_2$ spectrum analyzer; $P$, power meter; $G$, grating; PZT, piezoelectric ceramic transducer.

cause the higher pressure causes a reduction in $\tau_{1A}$. At the same time, the reduction of $\tau_{1A}$ also causes $S_{01}$ in Eq. (2) to reduce. Therefore, $R(\omega)$ in Eq. (2) increases with the enhancement of the air pressure when the system is modulated by a light field whose frequency is lower than $\omega_c$. At the optimal operation point, the best population distribution between the upper and lower levels is achieved. That point corresponds to the largest optogalvanic signal. The shift of $\omega_c$ means that the higher modulating frequency is available, which causes discharge noises to have a smaller impact to the optogalvanic current so as to improve the SNR dramatically.

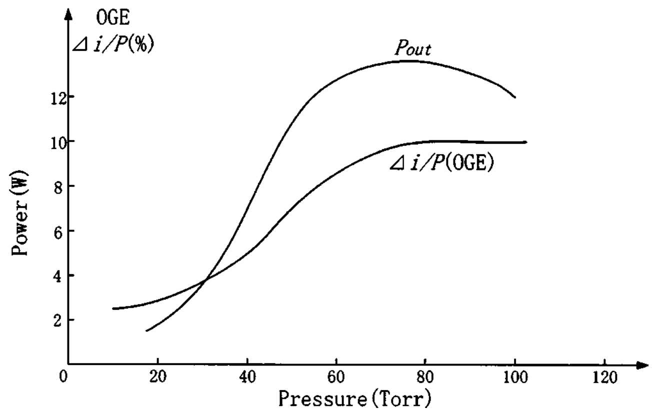


**Fig. 3** OGE as a function of pressure and output power: $P_{out}$, output power; $\Delta i/P$, OGE variation; $I=6$ mA, $f=1000$ Hz.

### 2.2.2 *Relationship of the optogalvanic signals and the discharge conditions*

In the measurement for the relationship of optogalvanic signals to the working pressure and the current, Fig. 4 shows that with a change of the working current the optogalvanic signals appear to have a largest value, corresponding to the best working current. Because the best working current has the highest upper level excitation rate and the lower level excitation rate is relatively low, the $S_{02}$ in Eq. (2) is improved greatly. Furthermore, compared with the conventional lasers with equal cavity length, the waveguide laser with much higher air pressure has an obvious advantage on the optogalvanic current because the high air pressure and the low current cause $\tau_{2A}$ to increase and $\tau_{1A}$ to reduce. Hence, the $S_{01}$ in Eq. (2) reduces sharply and $S_{02}$ increases at the same time. In other words, the total optogalvanic current amplitude $R(\omega)$ increases as well when $\omega$ is lower than $\omega_c$.

Obviously, the optogalvanic current characteristics of $CO_2$ waveguide lasers, such as the high sensitivity, the high amplitude, the high response frequency, and the high SNR, are quite favorable for the frequency stabilization.

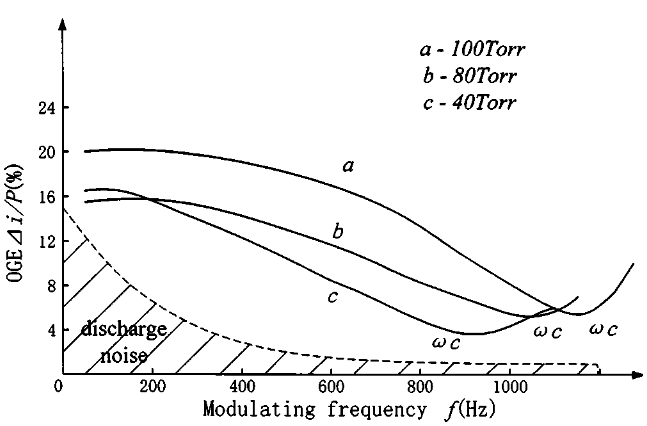


**Fig. 2** OGE as a function of modulating frequency and pressure: $\Delta i/P$, OGE change unit power; $\omega_c$, counter spot of frequency; $I$, operating current—8 mA.

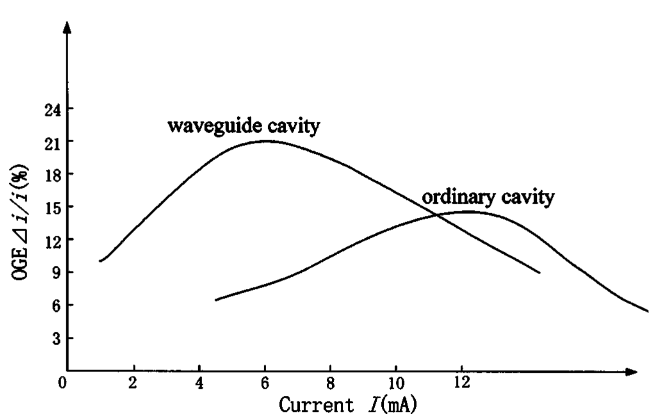


**Fig. 4** OGE as a function of operating current and pressure in an ordinary $CO_2$ laser: pressure $P=30$ Torr; waveguide $CO_2$ laser, pressure $P=80$ Torr, $f=1000$ Hz.

## 3 $CO_2$ Waveguide Lasers Stabilized by OGE and Tuned by the Compound Cavity

### 3.1 *Experimental Setup*

Combining our previous study on the $CO_2$ waveguide lasers with a compound cavity,[4] we set up a $CO_2$ waveguide laser system stabilized by the OGE and tuned by the compound cavity. Figure 1 is the general experimental setup including the grating compound cavity tuning and optogalvanic current frequency stabilizing servo control.

### 3.2 *Grating Compound Cavity Tuning (Branch Selection) System*

The cavity used for the frequency selection and the tuning of $CO_2$ waveguide lasers was often investigated by many people. However, some drawbacks exist in the cavities they proposed. For example, the resolution ratio and the coupling efficiencies of the conventional grating cavity are very low and the line-jumping phenomenon occurs in the process of frequency selection. Although the spherical grating cavity has a simple structure and good-quality beams, it is very hard to manufacture the spherical grating with a small radius. A Fox-Smith cavity has a relatively low loss and a high resolution, but its complicated structure and large size compromises the most favorable advantage of the waveguide lasers: miniaturization. Thus we proposed a special cavity for the continuous tuning of the $CO_2$ waveguide lasers; that is, a compound cavity composed of the grating $G$, the reflective mirrors $M_1$, $M_2$, etc. (see Ref. 4). This type of the cavity not only has a compacted structure, but it also has a high resolution and wide tuning range, and it can also completely avoid the line-jumping phenomenon. References 4 and 5 include a detailed presentation.

For wavelengths stratifying the ''Lettor'' condition, the grating $G$ is equivalent to a cavity mirror. It and partial transmission mirror comprise the ''F-P'' cavity (coupling cavity), and the ''F-P'' cavity and the totally reflecting mirror $M_2$ comprise the compound cavity. From the viewpoint of the resonator mirror reflection,[6] the coupling cavity is equivalent to a reflective mirror with a tunable reflective index $R_{\mathrm{tot}}$ (Ref. 7):

$$R_{\mathrm{tot}}=\frac{(r_1-r_3)^2+r_1 r_3 \sin^2 \phi_b}{(1-r_1 r_3)^2+4 r_1 r_3 \sin^2 \phi_b}. \tag{4}$$

In Eq. (4), $r_1$ and $r_2$ are the reflective indices of $M_1$ and grating $G$, respectively. The phase displacement $\Phi_b$ is $(2\pi/\lambda)L_1$. Hence, for the every spectral line that is chosen through the grating equation $\lambda=2d\sin i$, the optimal coupling efficiency of the resonator is obtained. Simultaneously, the $EH_{11}$ mode can be coupled into $TEM_{00}$ with quite low loss due to $M_1$ being as close as possible to the orifice of the waveguide tube.[8] A laser with a compound cavity therefore not only has a compact and safe structure, but also achieves continuous tuning and high power operation.

Here $G$ is an etched grating with a grating constant 120 lines/mm; the transmissive ratio of $M_1$ is 0.8; $M_1$ and $M_2$ are both planar mirrors; the coupling cavity length $L_1$ is 3 cm and the main cavity length (the distance between $M_1$ and $M_2$) is 30 cm. Also, $G$ is fixed on the substrate of the grating turret by the piezoelectric ceramic transducer. The branch selection procedure can be completed as follows:

1. The computer controls a stepper motor to rotate the grating so as to select 60 lines from the range of 9 to 11 $\mu$m.
2. For the every spectral line, the optimal output is obtained by modulating $L_1$ and controlling the voltage of the piezoelectric ceramic.

On the other hand, based on the principle of the compound cavity mode resonance proposed by Kong et al., the compound cavity phase change $\Phi_b$ not only influences the total equivalent reflective index of the compound cavity, i.e., $R_{\mathrm{tot}}$ in Eq. (4), but also causes[9] a phase change of the compound cavity oscillating modes $\delta_e$.

$$\tan \delta_e=\frac{(1-r_1)^2 r_3 \sin 2\phi_b}{(1+r_1^2) r_3 \cos 2\phi_b - r_1(1+r_3)^2} \tag{5}$$

Therefore, the accommodation to $L_1$ means tuning to the wavelengths of the oscillating modes, which is the basis for study of the tuning system.

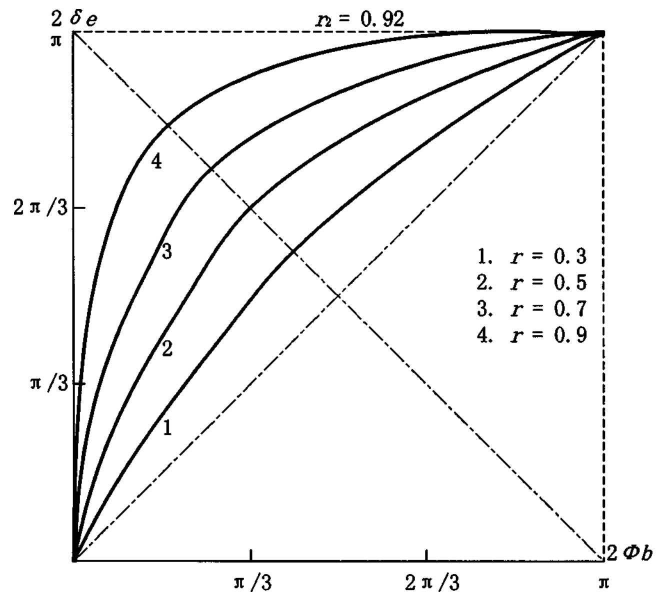

**Fig. 5** Equivalent reflectivity $r_1$ and its reflective phase change $\delta_e$ as a function of $\Phi_b$.

Figure 5 presents the relationship of curves $\delta_e$ and $\Phi_b$ as a result of Eq. (5), and shows that there is a sensitive area with the change of $\Phi_b$ for an appropriate transmission rate $r_1$ of $M_1$. Figure 6 represents the relationship of the laser output power (corresponding to $R_{\mathrm{tot}}$ of the compound cavity) and the displacement of the piezoelectric ceramic (corresponding to the coupling cavity length $L_1$). This shows that the modulation to $L_1$ is equivalent to the modulation to the cavity frequency and the field strength of the compound cavity. Similarly, the stability of $L_1$ means the stability of the output power and the oscillating frequency of the compound cavity lasers.

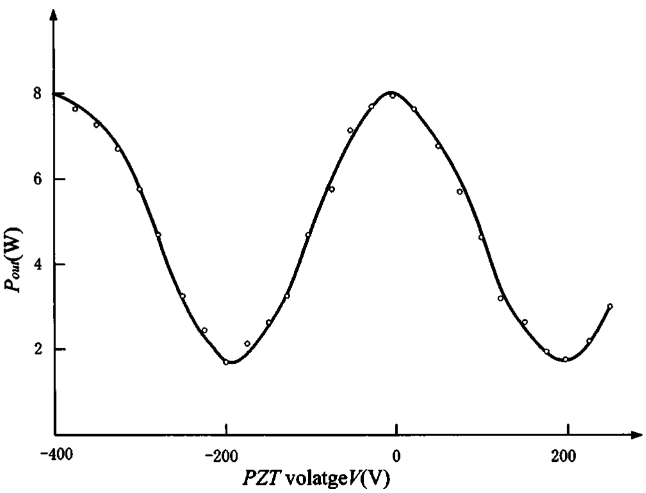


**Fig. 6** Output power as a function of displacement of PZT displacement: $\Delta L_1 = 8 \times 10^{-3}$ $\mu$m/V.

### 3.3 *Optogalvanic Current Frequency Stabilization and Servo Control System*

When the compound cavity tuning system finishes the branch selection process, the feedback control system for the optogalvanic current frequency stabilization begins the process of the frequency stabilization. A sinusoidal wave modulation voltage with $f = 1000$ Hz, output from an oscillator, effects the piezoelectric ceramic, which is in an optimal branch selection state, and then the radiation field modulation inside the laser cavity is formed as in Eq. (4) (the modulation quantity of $L_1$ is $\Delta L_1$, as in Fig. 6). Simultaneously, this also accompanies the modulation to the central frequency point of the oscillating wavelengths as in Eq. (5). With the influence of outside factors, the variation of the laser cavity causes a corresponding variation of the laser output power and its frequency.[10] In other words, it impacts on the discharge resistance of the discharge tube so as to obtain the corresponding error signals of the optogalvanic current variation.

As shown in Fig. 1, the whole frequency stabilization feedback system includes two parts: the optogalvanic current measurement and the servo feedback control. The optogalvanic current signals from the "$R_0C$" network is amplified by a preamplifier $D_1$ (gain$=10^4$) and then is input into the servo control system. To measure the tenuous signals, we use two series of the synchronic integrator and a series of the correlator for the synchronic integrated circuits and the phase-sensitive wave detection circuits PH, so the system has a good capacity to repress noise. The total gain of this part is higher than $10^4$ to reduce as much as possible the modulation quantity $\Delta L_1$ so that the laser operation stability is improved. The circuit's first series $\Sigma$ drove by the piezoelectric ceramic is the signal synthesis, including the output signals of the phase-clocked circuit, the oscillator modulation signals, the computer-control signals, and the voltage bias adjustment. The synthetic signal obtains the $\pm$400-V output through the emitter following the differential amplifier $D_2$. The gain of the whole servo circuit is $10^6$, the time for the circuit differential is 0.15 to 2 s.

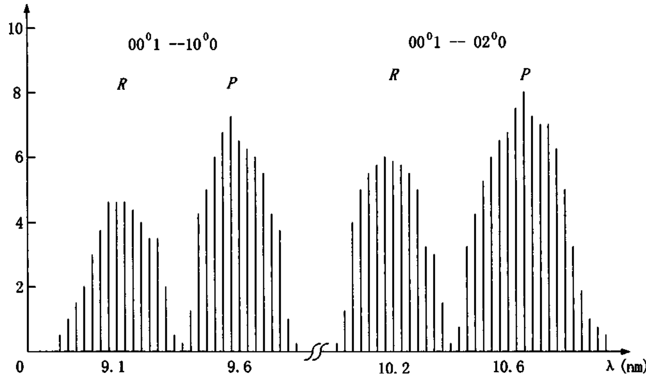


**Fig. 7** Observed laser emission spectrum current: $I = 8$ mA; pressure $P = 60$ Torr.

## 4 Conclusion

We used an advanced computer as the central control system of the whole device (expanding four interfaces and designing the control software) for the processes of the compound cavity branch selection (including the adjustment and the localization of the grating incident angle and the coupling efficiency of the coupling cavity) and the servo feedback control for the optogalvanic current frequency stabilization. The operation sequences are as follows.

First, 60 spectral lines were selected through the whole process of the compound cavity branch selection. They are:

$$00^01 \text{ to } 10^00: \quad P(12)-P(44), R(14)-R(42),$$

$$00^01 \text{ to } 02^00: \quad P(14)-P(44), R(16)-R(38).$$

The wavelength range of all the spectral lines is 9.183 to 10.860 $\mu$m; the largest single line [P(22)] power is up to 8 W. Figure 7 represents the output power of the laser spectral lines.

For the each output spectral line in the stable operation state, we used a sinusoidal wave with $f = 1000$ Hz and amplitude $\pm$50 V (equivalent to $\Delta L_1 = 0.8$ $\mu$m) to modulate the coupling cavity length $L_1$, and the time for the servo circuit integration is 0.3 s. We measured the each line's power stability in the every spectral band and obtained the power stability average value 0.8% of each output spectral line for a long-term (60-min) operation. Figure 8 shows the output power curve of the line $P(18)$.

For a $CO_2$ lasers with a single line operation, the resonator length is related to the laser output frequency and the output power. The frequency stability of the computing and analyzing system showed that the preceding frequency selection range of 9 to 11 $\mu$m was equivalent to a $\nu = 10^{13}$ MHz laser oscillating frequency. Assuming the average fluctuation value of the system output power as 0.8%, we could estimate the change of the compound equivalent cavity length to be $\Delta L \approx 3$ $\mu$m from Eq. (4) and Fig. 6. Under the condition that the system main cavity length is 30 cm, the corresponding single operation frequency stability is about $\Delta \nu / \nu = 10^{-9}$.

Due to the operation characteristics of $CO_2$ waveguide lasers, it is so hard to achieve the spectral line tuning and

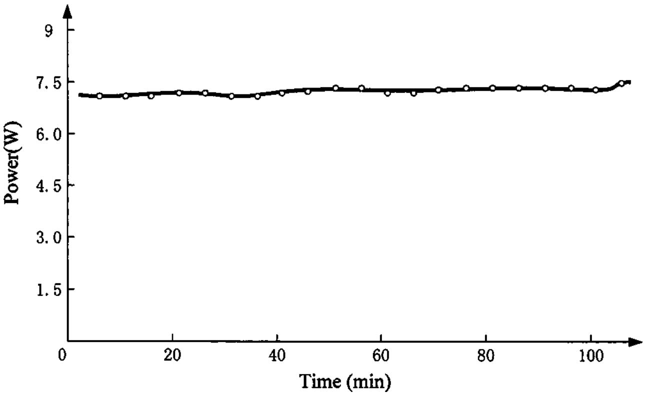


**Fig. 8** Single line power stability $00^01$ to $10^00$ transition $P(22)$ line, $I=6$ mA.

the line stability simultaneously if we adopt conventional methods, such as the spectrum absorption frequency stabilization method, the lamb-dip stabilization method, etc. Our study shows that the optogalvanic current frequency stabilization and the compound cavity tuning are effective approaches to develop tunable frequency-stabilized $CO_2$ waveguide lasers. Theoretical and experimental works have proved that the $CO_2$ waveguide laser has an obvious advantage with respect to the optogalvanic current. The favorable features of the grating compound cavity lie in a low loss on waveguide mode coupling, simple but safe structure, and tunable frequency and power. Just for these reasons, this type of laser system with this combination of these features can not only select out each branch of spectral lines easily, but can also achieve stability of the frequency and power of the spectral lines and attain an optimal power output in the end.

## Acknowledgments

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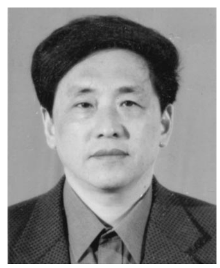

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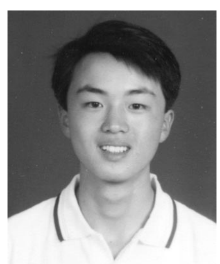

**Di Liang** is a senior student majoring in optoelectric information engineering and received his BS degree from the Department of Optical Engineering, Zhejiang University, in June 2002. He was originally admitted by the Department of Mechanical Engineering in 1998. A year later, he was qualified to transfer to his major to optoelectric information engineering based on his excellent academic record. Then he entered the Center for Optical and Electromagnetic Research and focused on the study of optoelectronic devices, optical communications, and lasers. He was awarded many academic scholarships by Zhejiang University and several of his papers have been accepted by domestic and international professional journals.

Waveguide lasers are lasers with a waveguide structure in the gain medium. Fiber lasers are the most prominent example.Â Waveguide structures are also used in some CO2 lasers. The advantages are that the transverse dimensions of the gas tube can be reduced so as to obtain efficient cooling of the laser gas, and that the obtained beam quality can be very high. Characteristic Properties of Waveguide Lasers.Â  D. Geskus et al., â€œHigh-power, broadly tunable, and low-quantum-defect KGd1âˆ'xLux(WO4)2:Yb3+ channel waveguide lasersâ€, Opt. Express 18 (25), 26107 (2010), doi:10.1364/OE.18.026107. (Suggest additional literature!) The issues of the frequency stabilization of lasers that operate in pulseâ€"periodic modes were considered less carefully because of the essentially higher fre quency instability, which is caused by changes in the discharge parameters during a pumping pulse. An exception is Đ¡Đž2 TEA lasers, for which, in order to attain a single frequency lasing mode, various meth ods for injecting stabilized radiation, as a rule, from a cw laser source, were developed [2].Â  This study presents a compact frequency stabilized pulseâ€"periodic CO2 laser for calibrating wavelength meters. The stabilization of the 10P(14) lasing line is performed using an external sealed off nonresonance. INSTRUMENTS AND EXPERIMENTAL TECHNIQUES Vol. 57 No. 2 2014. In recent years, waveguide CO2 lasers have been developed as compact sources of IR radiation with applications in spectroscopy, optical pumping, materials processing, and remote sensing. One important factor in their design is the control of transverse modes. The achievement of quasi- TEM00 transverse mode output is clearly very desirable for applications where the laser radiation is to be focused or propagated over any distance. Moveover, in applications where the precise optical frequency is a key feature, the control of the axial mode structure assumes great importance. These two objectives must be achieved simultaneously in a laser to be continuously tuned over a substantial frequency range. Â© 1984 Optical Society of America. PDF Article. More Like This. The CO2 laser frequency stability is up to 4.6 Ã— 10âˆ'8. The frequency stabilization control system owns advantages of small volume, compact structure. It can be also used for other type of lasers. View. Show abstract. Polarization and wavelength insensitive optical feedback control systems for stabilizing CO 2 lasers. Conference Paper. Mar 2016.Â Hollow waveguide gas lasers of the type described by Smith have some inherent loss in coupling radiation from the guide into free space and back into the guide. This paper calculates that loss for the EH 11 lowest order waveguide mode as a function of mirror position and mirror radius. It is shown that some mirror positions and radii are optimum, in that they provide low coupling loss and are relatively insensitive to mirror position.