Power Stabilization of the Dual-Mode Laser Using Volume Holographic Gratings

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Abstract—We present a power stabilization method for a dual-mode Ti:Sapphire ring cavity laser. Without stabilization, mode competition caused the output power of the two modes to fluctuate by approximately 10 dB. The power stabilization system, which used volume holographic gratings to monitor the power in each mode, reduced the power fluctuations to less than 3 dB.

Index Terms—Dual-mode laser, power stabilization, Ti:Sapphire laser, volume holographic gratings.

I. INTRODUCTION

The photonic techniques to generate GHz and THz frequency radiation by mixing the coherent radiation from two infrared lasers on a suitable photomixer is currently discussed often in the literature [1]–[3]. Such frequency sources find their potential applications in telecommunications, luggage screening, tomography, and astronomy, among others. In astronomy, they can be used as widely tunable local oscillators in heterodyne receivers. However, this application, unlike others, requires an outstanding stability of output power and frequency.

The generation of millimeter- and submillimeter-wave radiation using a dual-mode laser was demonstrated recently [3]–[8]. Although various types of lasers and laser frequencies were used, the common principle is the generation of two frequencies (dual-mode operation) in one laser resonator. Due to common-mode rejection [7] the drift in the beat frequency generated by the dual-mode laser is much smaller than the drift in the beat frequency generated by two individual lasers under identical conditions.

However, the power of each mode varies continuously mainly because of air fluctuations, thermal fluctuations, and strong mode competition [9], [10]. These power fluctuations cause power instability of the beat frequency signal generated by the photomixer. To improve the stability, we developed an active power stabilization system implemented in a Ti:Sapphire ring cavity laser with intracavity etalons to generate the two modes. Power stabilization is difficult since one must monitor independently the power of the two modes, which are closely spaced ($\Delta \lambda / \lambda$ equals 1/38000 for our laser). This requires very good and stable filters to separate the modes. We used volume holographic gratings (VHGs) to monitor the power of the two modes independently. VHGs are suited to this task better than etalons since etalons have periodic transmission curves that could pass multiple modes whereas the VHGs pass only single modes.

II. VOLUME HOLOGRAPHIC GRATINGS

The VHGs are a diffractive element that consists of a periodic phase or absorption perturbation throughout the entire volume of the element as shown in Fig. 1. When the incident beam satisfies the Bragg phase matching condition, it is reflected by the periodic perturbation [11] but other wavelengths pass through the VHG without dispersion [12]. The Bragg wavelength of the holographic grating is given by [13] as

$$\lambda_b = 2n(T_0)\Lambda(T_0) \cos \theta_n$$  \hspace{1cm} (1)

where $\lambda_b$ is the Bragg phase matching wavelength, $n(T_0)$ is the average refractive index of the material at temperature $T_0$, $\Lambda(T_0)$ is the holographic grating period at $T_0$, and $\theta_n$ is the angle of the beam inside the grating. By changing $\theta_n$, the Bragg wavelength can be varied continuously from $2n\Lambda$ down to $2\Lambda(n^2 - 1)^{1/2}$ [14].

The diffracted wavelength range, $\Delta \lambda$, is inversely proportional to the VHG effective thickness, $D$, and is given by [15] as

$$\frac{\Delta \lambda}{\lambda_b} = \frac{\Lambda \cot(\theta_n)}{D}.$$  \hspace{1cm} (2)

III. EXPERIMENTAL SETUP

Fig. 2 schematically shows the Ti:Sapphire ring cavity laser (Coherence Model 899) with the internal mode selection components and the dual-mode power-stabilization feedback loop that
we integrated. The birefringent filter with a full width half maximum (FWHM) of 1.7-THz determined the maximal passband in which the two modes could be selected. The effective round trip cavity length was about 1.6 m, giving a mode separation of about 184 MHz. The periscope mirror \( P \) and the collimation lens \( L \) were used to inject the 532-nm beam from the Coherent VERDI laser (Nd:YVO\(_4\) solid state laser with frequency doubler) into the ring cavity. The VERDI laser had a peak power of 5 W. The ring cavity consists of the curved mirrors \( M_1 \) and \( M_2 \) with the Ti:Sapphire crystal situated in between and the flat mirrors \( M_3 \) and \( M_4 \). The laser action in the counter-clockwise direction was suppressed by a Faraday rotator acting as an isolator.

The Ti:Sapphire ring cavity laser had a very wideband gain profile and had many longitudinal modes. The sinusoidal throughput of the birefringent filter, however, favored modes with highest gains near its peak transmission. Two modes near this peak with 100-GHz separation were selected by combining two solid Fabry–Perot etalons \( E_1 \) and \( E_2 \) with a free spectral range (FSR) of 100 and 10 GHz, respectively (see Fig. 3). In the figure, where the transmission peaks align, a cavity mode can be amplified. In this example, three modes would be selected but an additional birefringent filter allows only two modes to survive. The etalons were from B. Halle GmbH, Berlin, Germany. The etalon data are shown in Table I. Frequency tuning of the etalons was performed by fine tilting with fine-pitch micrometers.

For power stabilization, the thin etalon in the power stabilization feedback loop was additionally fast tuned by a piezo-actuator (PZT). Fine tilt adjustment of the etalon allowed us to control the relative power in the two modes since the resonance condition required exact wavelength alignment of the passband peaks of the two etalons but this alignment was easily degraded by external factors such as air circulation, thermal fluctuations, and acoustic vibrations. These shifts caused an imbalance in the filter transmission at the wavelengths of the two selected modes, which lead to mode competition suppressing one mode. Fast
KIM et al.: POWER STABILIZATION OF THE DUAL-MODE LASER USING VOLUME HOLOGRAPHIC GRATINGS 1319

Fig. 4. Schematic configuration of the power stabilization system using the VHGs. The two modes were separated by two VHGs and the powers were monitored independently. The power difference generated an error signal which was used to tilt the thin etalon via the PZT controller.

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<th>TABLE I</th>
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<tr>
<td>ETALON SPECIFICATION</td>
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<td>Thickness [mm]</td>
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<td>Etalon [E1]</td>
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<td>Etalon [E2]</td>
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Specification of the etalons installed in the ring cavity for selecting the two modes. The material used is fused silica with a refractive index of 1.456 at a wavelength of 780 nm. The flatness deviation is better than $\lambda/10$.

Tuning of the thin etalon compensated for this by maintaining the exact wavelength alignment of the two etalons and, hence, to maintaining equal transmission for the two modes.

Fig. 4 shows the configuration of the power stabilization system using the VHGs (Ondax, Inc., Powerblocker: PLR784.0-45-E-1000). The laser beam from the Ti:Sapphire laser that contains the two wavelengths $\lambda_1$ and $\lambda_2$ passed a 90%/10%-beam splitter. The 10% beam was used to monitor the laser output with an Anritsu MS9710C optical spectrum analyzer. The other beam was used for the power stabilization system. To facilitate phase-sensitive detection, the beam passed a 20-Hz chopper first before hitting the first VHG. Both VHGs had a specified reflectivity of 45% at $\lambda = 784.0$ mm. Hence, 45% of the power at $\lambda_1$ was diffracted from the first VHG to the photo diode $D_1$. The rest of $\lambda_1$ were transmitted by the first VHG to the second VHG where 45% of the power at $\lambda_2$ was diffracted to the photo diode $D_2$. The power signals $P_\lambda$ and $P_{\lambda}$ detected by $D_1$ and $D_2$, respectively, were fed to the lock-in amplifier (LIA) inputs $A$ and $B$. The LIA performed phase detection of the difference signal $A - B$ using the chopper reference signal. The output DC level of the LIA was proportional to $P_\lambda - P_{\lambda}$ and was used as the error signal. This was fed into a proportional-integral (PI) amplifier with an integration time of 1 ms. The PI amplifier output controlled the fine adjustment of the tilt of the thin etalon via the PZT controller and the PZT. The actuator was a S-316.10 from PI with a displacement of 0.12 $\mu$m/V and a bandwidth of 1 kHz. During measurements the error signal was recorded by a National Instrument Data Acquisition system (NI DAQ) controlled by a LabView program.

To demonstrate the 100-GHz beat frequency power, we used a photomixer developed at the Max-Planck-Institute for Radio Astronomy and processed on a GaAs wafer at the Research Center Jülich [16]–[18]. The emitted 100-GHz radiation power was measured by a Golay cell as shown in the schematic overview of Fig. 5.

IV. EXPERIMENTAL RESULTS

A. Spectral Bandwidth of the VHGs

A tunable diode laser was used to characterize the spectral behavior of the VHGs with a resolution of 0.005 nm. The result is shown in Fig. 6. The spectral bandwidth of the VHGs was approximately 0.2 nm (approximately 100 GHz). Fig. 6 also shows identical measurements at different angles of incidence (2°, 3.5°, 8° and 12°). As expected from the Bragg condition, the filter peak shifted to shorter wavelength and the spectral
bandwidth decreased with increasing tilt angle [see formulae (1) and (2)].

B. Dual-Mode Laser Operation

Two resonator modes were selected that had a difference frequency of about 100 GHz, determined mainly by the FSR of the thin etalon. The total output power of the laser was around 200 mW at maximum. The spectrum observed with the optical spectrum analyzer is presented in Fig. 7. Note that the FWHM of the two laser lines was determined by the laser resonator and can be of the order of ten kHz within a few milliseconds.

C. Beat Frequency Power

To avoid damaging the photomixer at the applied bias voltage of 7 V, the laser power at the mixer was kept under 35 mW. With this laser power, the maximum radiation power at 100 GHz was 70 nW with fluctuations of 20% mainly because of the remaining power variations between the modes.

D. Power Stabilization Using the VHGs

A typical error signal at the output of the PI amplifier is shown in Fig. 8.

Fig. 9 shows the peak power difference between two modes recorded for 600 s periods by the optical spectrum analyzer. The integration time was 1 s. In the case of operation without the power stabilization system, the fluctuations in the power difference were ~10 dB with occasional excursions to 30 dB. As presented in the Fig. 9, the fluctuations in the power difference with the power stabilization system were less than 3 dB, except for a few moments. It is clearly shown that the power stability was improved when the power stabilization system was on. By comparing Figs. 8 and 9, one notes that the times of the peaks are identical. However, the peaks that appear indicate single-mode
operation for very short periods of time. An explanation of this behavior is hard to give here, but the events occurred too fast for the servo system to correct.

E. Beat Frequency Stability

The stability of the 100-GHz mixing product could not be observed directly because RF measurement equipment was not available above 50 GHz. Therefore, to measure the beat frequency stability, we analyzed the mixing product at 34 GHz. For the experimental setup, 3- and 12-mm etalons with reflectivity of 20% were installed to select two modes which were mixed by a commercial photomixer made by New Focus (Model number 1004) which has 32-nW (≈45 dBm) output power when the input power is 0.8 mW at 780-nm wavelength. The frequency drift was recorded by an Agilent RF spectrum analyzer with resolution of 910 Hz. As shown in Fig. 10, the 34-GHz beat frequency drift was ≈50-kHz maximum over 3 h.

It is not expected that mode hopping played an important role in the stability of the beat frequency for two reasons. First, the birefringent filter allowed only a few modes to pass, so the scope for mode hopping was very limited. Second, were the filter passband to drift, then both modes in the passband would hop together, thus producing no change in the beat frequency. This expectation was confirmed by the 34-GHz beat frequency stability.

The stability of the 100-GHz mixing product was inferred indirectly by recording the wavelength of the peak intensities of both modes with the optical spectrum analyzer at regular intervals over 600 s. The wavelengths of the two modes were differentiated to infer the beat frequency. Fig. 11 shows the behavior of the inferred beat frequency with the servo loop off and on. In Fig. 11, the dispersion of the difference frequencies is caused by the noise of the optical spectrum analyzer. The outliers are moments when one mode was suppressed. The inferred beat frequency changed by no more than $2.4 \times 10^9$ Hz over 300 s (standard-error of the mean) without power stabilization and $1.6 \times 10^9$ Hz over 300 s (standard-error of the mean) with power stabilization. These fluctuations were dominated by noise in the optical spectrum analyzer and the stability of the beat frequency is probably much better than these upper limits. This shows that the fast tilting of the thin etalon with the servo loop on did not degrade the stability of the 100-GHz beat frequency by more than the $1.6 \times 10^9$ Hz noise of the optical analyzer.

V. CONCLUSION

We presented a power stabilization method for a dual-mode Ti:Sapphire laser. The experiment showed that the power fluctuations were reduced considerably.
To improve the power stability further, the etalons should be made of a low thermal expansion material such as diamond (with the very high thermal conductivity of $k > 2500$ W/m K). Also, an air-spaced etalon with spacers from low thermal expansion material such as Invar or Zerodur [19], mounted in a pressure-tight housing, could improve stability. Further, a power stabilization system should be considered with, for example, a thermostatic housing, which would also help to reduce acoustic effects.

REFERENCES


