Flight qualification of a diode laser for path difference determination of a high-resolution Fourier transform spectrometer

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Diode lasers offer a lightweight, rugged, and economic alternative to other types of laser source, but they often do not provide long-term stability and spectral purity of emission. We have developed a stabilized, near-infrared diode laser source that is capable of as much as 20 mW of single-mode output power for the effective replacement of a He–Ne laser in the path difference measuring system of a high-resolution (1.25-m maximum path difference) Fourier transform spectrometer. Laser characterization has been performed both in laboratory measurements and in flight tests, resulting in a relative frequency stability of better than 10^{-6} on a 6-h flight. © 2000 Optical Society of America

OCIS codes: 300.6300, 140.2020.

1. Introduction

In high-resolution Fourier transform (FT) spectrometry a reference laser interferometer is used for optical path difference measurements.[1–3] The laser source can be a critical component if we consider field and aerospace applications.[4–6] From this point of view the development of a solid-state alternative to He–Ne lasers is particularly interesting. An ideal laser source for path difference measurements should have enough coherence length to permit interference with good fringe contrast for the whole path difference range. Furthermore, this source should have good long-term frequency stability, at least for the acquisition of a single interferogram to avoid sampling errors. If we want a long-term frequency calibration and spectral averaging capability the source should be usable for all path difference measurements.

Given a maximum path difference z_{max}, the laser linewidth $\Delta \nu_L$ must be narrow enough to have a coherence length of $l = c/\Delta \nu_L$ that is greater than z_{max}. So we must have a linewidth $\Delta \nu_L < c/z_{max}$ to observe interference during the entire scan. In the presence of a laser wavelength fluctuation $\delta \nu_L$, the phase error in the laser interferometer is given by

$$\delta \phi_L = 2\pi n \frac{\delta \nu_L}{\nu_L} = \frac{2\pi z}{c} \delta \nu_L, \qquad (1)$$

where z is the path difference, ν_L is the laser optical frequency, and n is the interference order (the number of fringes counted from zero path difference). If ν_0 is the frequency of a monochromatic source measured with the FT spectrometer and λ_0 is the corresponding wavelength, the phase error during the sampling of the source is equal to

$$\delta \phi_0 = \delta \phi_L \frac{\nu_0}{\nu_L} = \frac{2\pi z}{\lambda_0} \frac{\delta \nu_L}{\nu_L}. \qquad (2)$$

If we consider that in FT spectrometry the maximum sampling error, expressed in terms of phase, is given by $\delta \phi_0 \sim \pi/\text{SNR}$, where SNR is the spectral signal-to-noise ratio, we believe that the relative frequency stability of the laser source for the acquisition of a single interferogram should be

$$\frac{\delta \nu_L}{\nu_L} \leq \frac{\lambda_0}{2\pi z} \delta \phi_0 = \frac{\lambda_0}{2 z_{max} \text{SNR}}. \qquad (3)$$

Bearing in mind that $\Delta \nu_R = c/2 z_{max}$ gives the spectral resolution of a FT spectrometer, we can express

Table 1. Characteristics of the Two FT Spectrometers used to Test the Laser System

Characteristics	IBEX	SAFIRE-A
Platform	Balloon	Aircraft
Flight height	~38 km	~20 km
Instrument type	Polarizing FT	Polarizing FT
Spectral operating range	7–180 cm^{-1}	10–250 cm^{-1}
Spectral resolution	0.0025 cm^{-1}	0.004 cm^{-1}
Maximum path difference	200 cm	125 cm
Acquisition time	180 s	15–60 s

Eq. (3) in terms of the resolving power $R = \nu_0/\Delta\nu_R$ of the instrument:

$$\frac{\delta\nu_L}{\nu_L} \le \frac{1}{R\,\mathrm{SNR}}. \tag{4}$$

With regard to long-term stability, we must take into consideration that a laser frequency variation of $\delta\nu_L/\nu_L$ gives an equal variation of $\delta\nu/\nu$ in the frequencies measured with the spectrometer. Therefore, if we want to achieve single-frequency calibration for the entire series of measurements, long-term relative laser stability should be

$$\frac{\delta\nu_L}{\nu_L} \ll \frac{\Delta\nu_R}{\nu_0} = \frac{1}{R}. \tag{5}$$

In practice the long-term stability requirement of inequality (4) is comparable with the short-term stability requirement of Eq. (3). However, some relaxation of the long-term requirement is considered to be acceptable if frequency calibration can be performed periodically.

2. Instrumental Requirements

The laser system has been developed to be mounted upon two different FT spectrometers that operate from a stratospheric platform: a balloonborne instrument, (IBEX (Infrared Balloon Experiment[7]), and an aircraft instrument, SAFIRE-A), (spectroscopy of the atmosphere using far infrared emission-airborne[6]). The characteristics of both instruments are summarized in Table 1. The laser stability requirements can be derived from these characteristics. If we use the SAFIRE-A instrument with 120-cm^{-1} (approximately 80-μm) channels and an expected SNR of 1000, from Eq. (3) and inequality (4) we obtain

$$\frac{\delta\nu_L}{\nu_L} < 3 \times 10^{-8} \ (\delta\nu_L < 10\ \mathrm{MHz}) \tag{6}$$

for a short-term time scale (i.e., a duration of ~1 min for a single acquisition), and

$$\frac{\delta\nu_L}{\nu_L} \ll 3 \times 10^{-5} \ (\delta\nu_L \ll 10\ \mathrm{GHz}) \tag{7}$$

for a long-term time scale, which is approximately 4−6 h for the entire flight. When we took into consideration the coherence length requirements, we de-
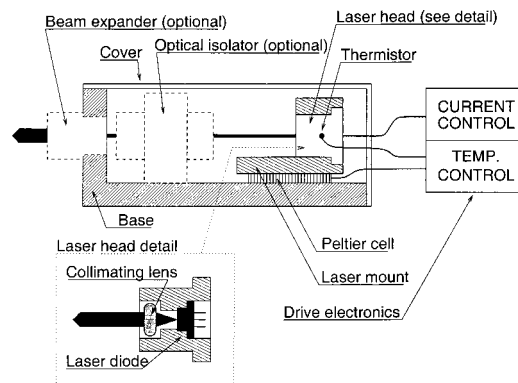

Fig. 1. Laser mechanical mounting. The laser head and the mounting block are made of Invar. We achieved thermal stabilization with the Peltier cell and the thermistor. An optical isolator and a beam expander can be incorporated into the system.

termined that the laser linewidth for $z_{\max} \sim 1.5$ m should be 200 MHz or less.

3. Laser Setup

Our laser system is based on a single-mode 780-nm diode laser (Sharp LT024MD) collimated by an antireflection-coated aspheric lens (Thorlabs C230TM with 0.55 numerical aperture and $f = 4.5$ mm). These two components are mounted in a cylindrical support (enlarged detail shown in Fig. 1) that fits into a block bolted to the interferometer frame. This scheme permits laser head interchangeability with minimum alignment loss. Both the laser head and the support are made of Invar to obtain good mechanical stability even when the operating temperature varies. As shown in Fig. 1, our laser setup indicates that an optical isolator can be used to eliminate optical feedback from the interferometer and a beam expander can be used to improve beam collimation. Nevertheless our results were obtained without these two devices.

We achieved thermal stabilization of the laser head and the mounting block by means of a feedback circuit that reads system temperature on a thermistor positioned as near as possible to the laser diode. The circuit drives a Peltier cell that controls the temperature over a wide range of temperatures. The same circuit board also contains the laser current driver. The laser operating current is 50 mA for an output power of approximately 10 mW. To avoid water vapor condensation during operation in wet climates, we used a stabilized temperature of 20 °C.

The laser temperature/current driver is a custom-made design specially developed to maintain maximum stability in flight conditions, i.e., wide ambient temperature excursions and the presence of electromagnetic interferences. To derive specification requirements for our control circuit we observed that laser wavelength λ_L is strongly dependent on both laser diode temperature and drive current. The temperature coefficient of λ_L is 0.1 nm/K, the dependence on drive current is 0.08 nm/mA. The details

Table 2. Review of the Laser Driver Circuit Performances[a]

Parameter	A	B
Long-term I_L stability	<1 μA	<40 MHz
I_L temperature coefficient	40×10^{-6}/K	80 kHz/K
T_L stabilization error	<1 mK	<50 MHz
T_L thermal coefficient	0.0004 K/K	20 MHz/K

[a]*A,* laser driver circuit performances with regard to laser drive current (I_L) and laser stabilization temperature (T_L). *B,* corresponding laser frequency stability. Long-term corresponds to approximately 1 h, temperature coefficients are expressed in terms of electronic temperatures.

of the laser driver circuit are listed in Table 2. It should be noted that neither the laser nor the electronic box need to be pressurized for low-pressure operation at stratospheric altitudes.

4. Experimental Results

To verify that the requirements established in Section 2 were performed, we measured the linewidth of the laser with a Fabry–Perot resonator (1.5-GHz free spectral range and >1000 finesse for an instrumental linewidth of approximately 100 kHz), resulting in less than 50 MHz. Furthermore, it is possible to verify a frequency stability to within a fraction of the linewidth for short-term observation of the order of a few minutes. In contrast, this method cannot be used to obtain accurate characterization of long-term stability, because of Fabry–Perot resonance fluctuations. One can best achieve long-term characterization by analyzing spectral data acquired during laboratory measurements and test flights. We performed several ground tests by mounting our laser onto the two different FT spectrometers, IBEX and SAFIRE-A, whose characteristics are summarized in Section 2.

Flight characterization of the laser system was performed on the SAFIRE-A instrument for a total of five aircraft flights (more than 20 h of acquisition). During each flight, as expected, the laser system suffered a thermal excursion of several degrees. The temperatures of the driver electronics and of the laser box recorded during the flight are reported in Fig. 2. The temperature stabilization error signal and the laser power output are also shown in Fig. 2.

From the data shown in Table 2 we can estimate the systematic error that is due to the driver electronics thermal coefficient. The predominant contribution comes from the temperature stabilization circuit: for a 4 K thermal excursion of the electronics box we deduce an 80-MHz drift in laser frequency. Note that this contribution is not included in the temperature error signal.

With reference to Fig. 2, taking into consideration that the conversion factor for temperature error is approximately 2.5 a.u. (arbitrary units)/K, we deduce a temperature drift of the laser head of approximately 7 mK. Using the temperature coefficient of λ_L equal to 0.1 nm/K (approximately 50 GHz/K in terms of laser frequency) translates into
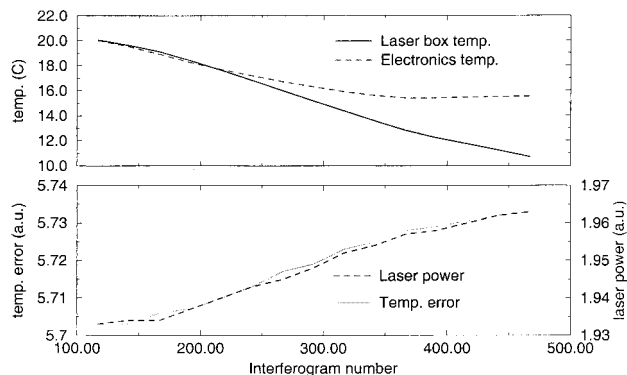

Fig. 2. Typical laser system temperatures and operating parameters as recorded during one of the test flights. The temperature of both the laser and the electronics boxes is in degrees celsius. Output power is expressed in arbitrary units (the average value corresponds to approximately 10 mW). The temperature error signal has a conversion factor of approximately 2.5 a.u. (arbitrary units)/K. The duration of the flight was 5 h 20 min.

350 MHz of laser frequency drift during flight time (5 h 20 min). The observed output power drift is also due to laser temperature variation, as can be easily seen from the correlation between the output power and the temperature error. Laser frequency stability has been measured directly from atmospheric spectral line frequencies. If ν_a is the center frequency of a single atmospheric line and ν_a^m is the corresponding measured value, we have $\delta\nu_a^m/\nu_a^m = \delta\nu_L/\nu_L$.

We obtained line centers from spectra acquired with the same acquisition parameters (observation angle, acquisition speed) by means of a fitting program. The results of the procedure are shown in Fig. 3 for two different atmospheric lines near 118 cm^{-1}. It is worth noting that the real laser stability effect should be a slow drift of the line center, because the main cause of laser frequency variation is the thermal excursion experienced by both the laser head
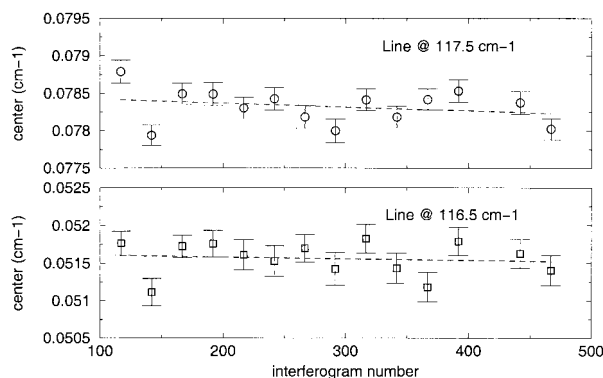

Fig. 3. Measured center frequencies (in terms of wave numbers) of two different atmospheric lines observed in similar conditions during the flight. The graph also shows a linear fit to visualize the line center drift that is due to thermal excursion: approximately 10^{-4} cm^{-1} in 5 h 20 min for both lines.

and the electronics. From the temperature readings of Fig. 2, we can approximate this drift as linear. This assumption is also confirmed by the short-term stability observed in the laboratory tests with the Fabry–Perot cavity.

From a linear fit of line centers (see Fig. 3) we deduce a line center drift of the order of 10^{-4} cm^{-1}, which, in terms of laser frequency, corresponds to approximately 300 MHz in 320 min. We can also scale this measurement of the long-term drift to derive the variation for a shorter time. We can confirm that the requirement of inequality (4) is satisfied for a duration of approximately 10 min.

In conclusion, we have built a diode laser source that is completely compliant with the requirements needed for a reference source to be used in high-resolution Fourier transform spectroscopy from stratospheric platforms, as results from a complete characterization performed both by laboratory and flight tests. This source proved to be a lighter, smaller, and cost-effective alternative to He–Ne lasers with all the advantages of solid-state devices and no need for a pressurized enclosure.

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