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Vienna, AUSTRIA, 2000, September 25-28

SIGNAL PROPERTIES OF MONOLITHIC ND:YAG LASERS

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Abstract: Monolithic Nd:YAG lasers are appropriate coherent light sources for measurement purposes. Measurement restrictions can be caused by laser signal instability. We discuss the influence of pump source, temperature and competing laser oscillations on signal properties of lasers with a linear resonator configuration and analyze some passive stabilization precautions. We conclude linear monolithic Nd:YAG lasers can provide high beat frequency stabilities which are comparable to optical stabilities of free-running nonplanar monolithic ring lasers.
*Keywords: Photonic Measurement, Nd:YAG Laser, Signal Stability*

1 INTRODUCTION

Recently diode-pumped solid-state lasers, especially Nd:YAG lasers, gain increasing importance for measurement purposes. Using this technology, miniaturized monolithic lasers with dimensions of some cm down to sub-mm can be realized. In lasers with nonplanar ring resonators all laser modes except one fundamental mode in a given propagation direction and with a given polarization can be suppressed. Such lasers offer high stabilities of the light frequency [1]. With linear resonator configurations two-frequency operation can be achieved. Here, the beat frequency between the two laser modes can be used for high-resolution measurements [2]. The spectral width of the Nd:YAG gain curve is very high (about 100 GHz). This has the disadvantage that an active frequency stabilization [3], [4] needs high effort and therefore is often not suitable for measuring applications. Otherwise this is advantageous especially for two-frequency lasers because a broad measurement range is available for detecting the measurand. Thus, we investigate how to achieve a high signal stability for lasers with linear resonator configuration using only passive measures.

2 LINEAR LASER SETUP

Fig. 1 shows the typical setup of a monolithic Nd:YAG laser with plano-concave linear resonator configuration suitable for two-frequency operation. The Nd:YAG crystal is optically pumped by means of a single-mode laser diode with the pump power P_P at the pump wavelength λ_P. The resonator mirrors are realized by high-reflection coatings on both sides of the crystal. By frozen mechanical stresses in the crystal and in the coatings a resonator-internal phase difference D is present. Due to D, the resonator is optically anisotropic and every laser mode of the isotropic resonator splits into two orthogonally polarized partial modes. Thus, the laser emits the powers P_1, P_2 at the emission wavelength λ_L with different frequencies ν_1, ν_2.
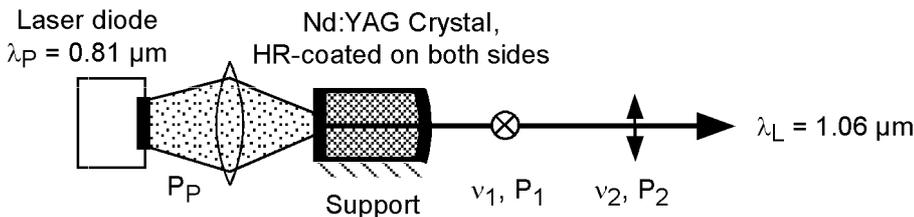
Figure 1. Monolithic Nd:YAG laser.

The beat frequency f of the two laser modes, which is often the interesting magnitude for measuring purposes, depends on the Free Spectral Range FSR of the resonator and the intracavity phase difference D:

$$f = \nu_1 - \nu_2 = \frac{\Delta \cdot FSR}{180°} \quad \text{with } FSR = \frac{c}{2 \cdot n_0 \cdot L} \quad \text{and } \Delta = \frac{\Delta n \cdot L \cdot 360°}{\lambda_L} \tag{1}$$

ν_i: mode frequency, $c = 3 \cdot 10^8$ m/s: velocity of light in vacuum, n_0: refraction index (YAG: $n_0 = 1.82$ [5]), L: geometrical length of the resonator, Dn: birefringence. The polarization directions of the laser modes are parallel and perpendicular to the main-axis orientation of the optical anisotropy.

For resonator-internal measuring principles the linear dependence of the beat frequency f on the phase difference Δ is purposively used. Applications are for example force measurement with monolithic Nd:YAG lasers [2] or ER-doped fiber lasers [6] by means of the photoelastic effect. For a crystal with the dimensions ø3 mm × 5 mm the sensitivity is about 30 MHz/N. In case of this measurement method, merely the beat frequency f and the light polarization are of interest. To evaluate the laser output the two laser modes are superposed by a polarizer and detected by a photodiode. Thereafter, the beat frequency f can be determined from the electrical output signal of the photodiode e.g. with a frequency counter, a spectrum analyzer, or a frequency-to-voltage converter.

3   INFLUENCES ON THE LASER RADIATION

We have purposively investigated laser output radiation of monolithic Nd:YAG lasers with linear resonators. Here we discuss the most important parameters influencing the laser radiation.

3.1   INFLUENCES OF THE PUMP SOURCE

The resonator-internal measurement principle requires only small pump powers P_P in the range of some milliwatts. Therefore, the thermal lens and the heating of the crystal caused by the pump power can be neglected.

The radiation of the pump source is linearly polarized. Using a rotatable half-wave plate between laser diode and Nd:YAG crystal, the polarization direction α of the pump radiation can be rotated. At $\alpha = 0°$, the polarization direction of the pump radiation and the main-axis orientation of the phase difference **D** are parallel. We measured the dependence of the powers P_1, P_2 of the two laser modes and the beat frequency f on the polarization direction α (Fig. 2).
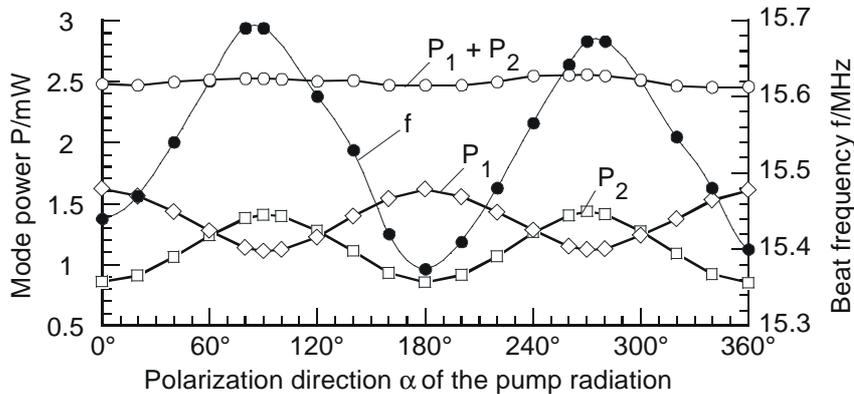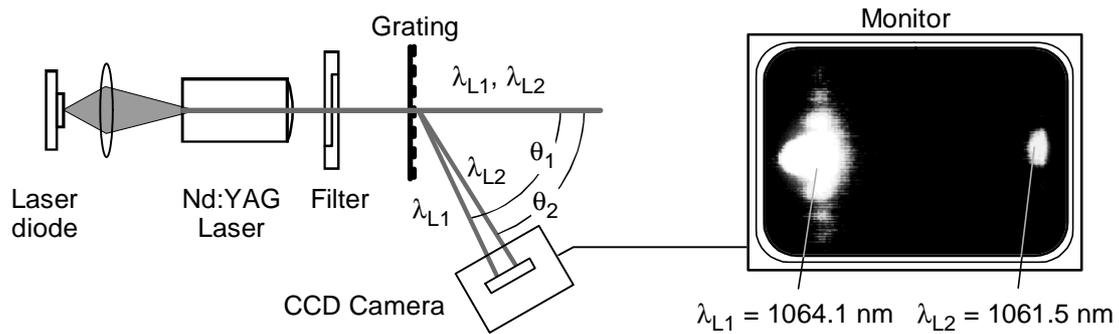
Figure 2.   Dependence of the mode powers P_1, P_2 and the beat frequency f on the polarization direction α of the pump radiation.

We observed a periodic dependence (period 180°) of the mode powers P_1, P_2 and the beat frequency f on the pump polarization direction α. The beat frequency f fluctuates by about 300 to 400 kHz. Eventual changes in the mode polarizations does not influence the measurement of the beat frequency. There are opposite changes in P_1 and P_2, i. e. when P_1 increases, P_2 decreases. The sum $P_1 + P_2$ of the mode powers remains nearly constant. To our knowledge, the influence of the pump polarization on the mode powers and the beat frequency is described here for the first time. Until now, a theoretical explanation of the effect has not yet been found.

Furthermore, the pump wavelength λ_P influences the beat frequency f. We carried out investigations where the wavelength λ_P is varied by changing the current I of the laser diode. The pump power P_P is kept constant by inserting an adjustable absorber between laser diode and Nd:YAG crystal. We found an approximately linear dependence of f on λ_P. The determined sensitivity is $Df/D\lambda_P = 160$ kHz/nm.

3.2   INFLUENCES BY SEVERAL LASER WAVELENGTHS λ_L

According to Eq. (1), the phase difference **D** depends on laser wavelength λ_L. Theoretically, Nd:YAG can produce laser radiation at several emission wavelengths. Under normal conditions (room temperature) the strongest laser line at 1064.1 nm has the lowest threshold [5]. However, if this laser line is suppressed by means of intracavity etalon a second laser line at 1061.5 nm has 92% of the output power of the first laser line without an intracavity etalon [5]. Therefore the radiation of an Nd:YAG laser was tested with a grating spectrograph (Fig. 3). In this spectrograph the laser radiation of the Nd:YAG laser irradiates a filter and a grating. The filter blocks the radiation of the pump source, the grating diffracts the laser radiation. A CCD-camera and a monitor are used to visualize the diffraction patterns.

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Figure 3. Setup for the grating spectrograph.

Even at room temperature, the monitor picture in Fig. 3 demonstrates a simultaneous emission at two wavelengths λ_{L1}, λ_{L2}. The output power at the wavelength λ_{L1} is much greater than at λ_{L2}. The corresponding diffraction angles θ_1, θ_2 of λ_{L1}, λ_{L2} are

$$\sin \theta_i = \frac{m}{a} \cdot \lambda_{Li} \tag{2}$$

(i = 1 or 2, a: grating constant, m: diffraction order). For our measurements we use the diffraction order m = 6 and a grating with a = 8 µm. The measured angles of θ_i lead to an emission at λ_{L1} = 1064.1 nm, λ_{L2} = 1061.5 nm.

Different beat frequencies f_1, f_2 at the wavelengths λ_{L1}, λ_{L2} follow from Eq. (1):

$$\frac{\lambda_{L1}}{\lambda_{L2}} = \frac{f_2}{f_1} \tag{3}$$

For small changes in the laser wavelength (λ_{L1} λ_{L2}), only small changes in the beat frequency f occur (f_1 f_2). In this case Eq. (3) can be transformed into

$$\frac{\Delta\lambda}{\lambda_L} = -\frac{\Delta f}{f} \tag{4}$$

with λ = λ_{L1} - λ_{L2},   f = f_1 - f_2. With λ_{L1} = 1064.1 nm, λ_{L2} = 1061.5 nm relative changes f/f = 2.5 · 10^{-3} in the beat frequency follow from Eq. (4). We measured the spectrum of the beat frequency with a spectrum analyzer and could separate two different beat frequencies f_1= 134.8 MHz, f_2 = 135.1 MHz. These values are in good agreement with Eq. (4). In this case of simultaneous operation at two wavelengths, a frequency counter or a frequency-to-voltage converter would deliver incorrect values for the beat frequency.

3.3   INFLUENCES BY MULTIMODE OPERATION

In principle, oscillation of a single longitudinal TEM_{00} mode order at a single wavelength is desired. Because of spatial hole burning, with Nd:YAG and a sufficient resonator length, more than one longitudinal mode order occurs. Additionally, oscillation of higher transverse modes is possible.

The spectral width of 100 GHz of the gain curve of Nd:YAG corresponds to a change of λ = 0.377 nm in the laser wavelength λ_L. According to Eq. (4), this causes relative changes of f/f = 3.5 · 10^{-4} in the beat frequency.

The light of higher transversal modes irradiates different parts of the laser crystal compared to the TEM_{00} mode. Therefore, the spatial distribution of the phase difference   in the crystal leads to a different beat frequency f.

3.4   TEMPERATURE INFLUENCES

Temperature fluctuations are by far the most important error source. Using a heatable chamber, different small-scale temperature test signals with maximum temperature changes of about 2°C are realized. This simulates an environment suitable for high-precision measurements. The different temperature test signals were achieved by different temporal courses of the heating power. Fig. 4 shows the measurements with a single cylindric laser crystal with the dimensions ø3 mm × 5 mm and two different temperature test signals, generated by triangle and rectangle heating, resp.
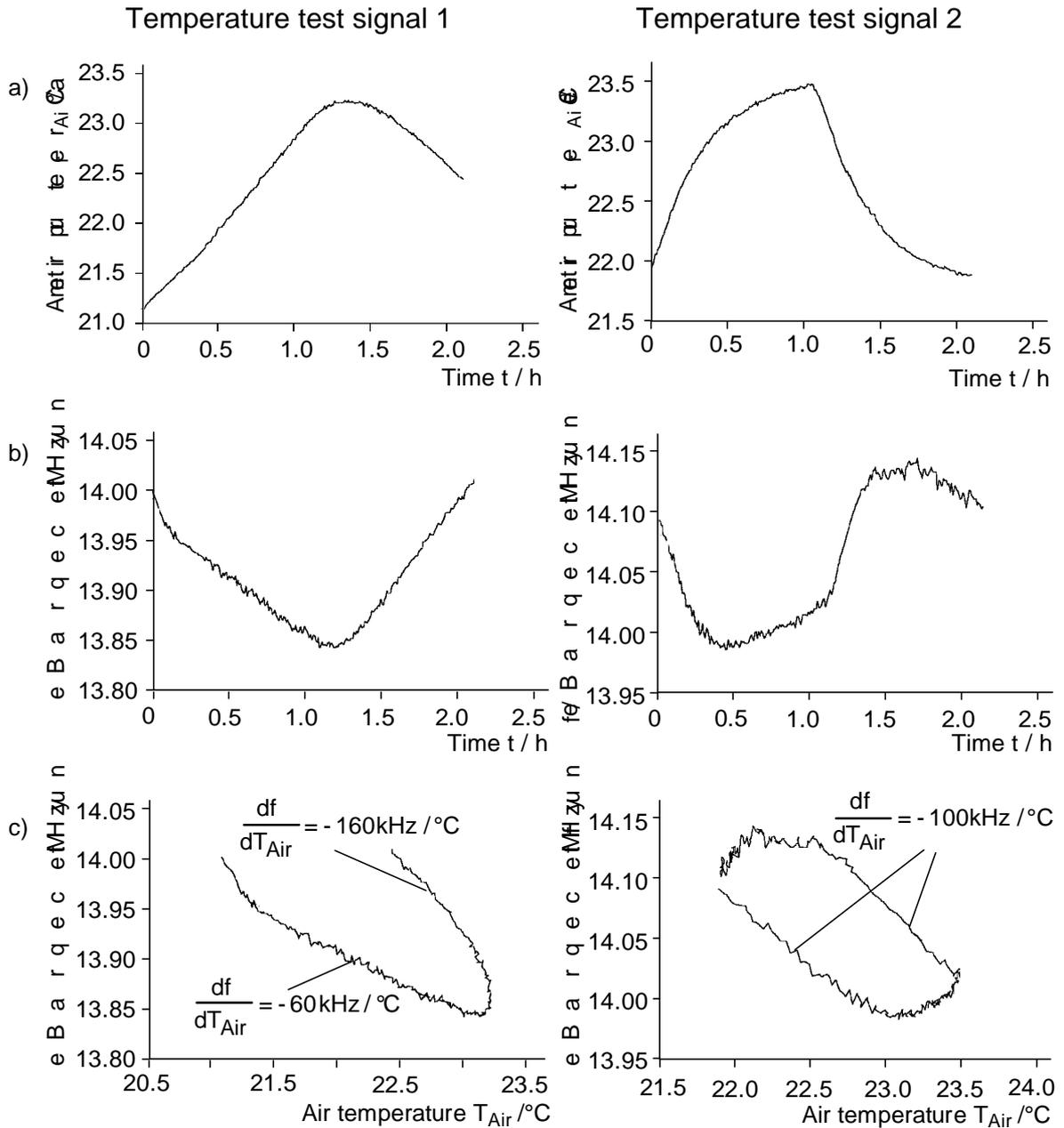
Figure 4. Investigation of the dependence of the beat frequency f on the air temperature T_{Air} with two temperature test signals: a) time dependence of air temperature, b) time dependence of beat frequency; c) dependence of beat frequency on air temperature. Crystal dimensions: ø3 mm × 5 mm.

    With both test signals changes in beat frequency of approximately 150 kHz are determined. The dependence of the temperature T_{Air} of the surrounding air on the beat frequency cannot be described by a simple linear equation. Different temperature coefficients df/dT_{Air} occur. The beat frequency f is not only influenced by the absolute temperature but also by its temporal derivative.

    Analogous measurements were carried out with approximately 10 other crystals having the dimensions ø3 mm × 5 mm. It turns out that every crystal has its own individual properties, even in the case of identical crystal dimensions. Changes in beat frequency between 10 and 200 kHz were determined. There is no relationship between phase difference   and the temperature-induced changes in the beat frequency. To explain the amount of the changes in the beat frequency thermal-induced stresses are not sufficient. The crystal anisotropy is also temperature-dependent and predominates the effect of the thermal-induced stresses in the laser material. There are indications that the main cause for the temperature dependence has to be looked for in the anisotropy of the coatings. Important indications are measurements with loaded crystals [7]. Using crystals with the dimensions ø3 mm × 5 mm at beat frequencies up to at least f = 200 MHz, the temperature behavior is independent of load and of f, resp.

4   STABILIZATION OF THE RADIATION PROPERTIES
We have taken the following measures to increase the stability of the laser radiation.

4.1   TEMPERATURE STABILIZATION
In Chapter 3 we found that the influence of the temperature is the most important error source. Therefore we tested a temperature-stabilized housing for the laser crystal, Fig. 5.
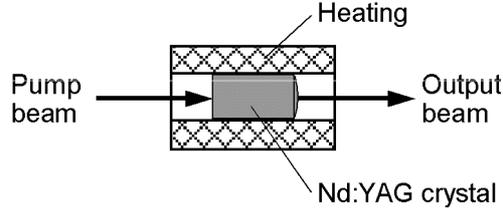
Figure 5.   Temperature-stabilized housing for the laser crystal.

With this temperature-stabilized housing, the temperature of crystal's cylindrical surface is kept constant above room temperature by means of a heating. The temperature variations at the cylindrical surface are reduced below 0.01°C. The front and the rear endface of the crystal remain unstabilized to enable the irradiation of the pump beam and the emission of the laser beam. This setup diminishes the temperature influences on the beat frequency f by about the factor four only. This is another indication that the temperature dependence of the beat frequency is caused by the coatings on both endfaces of the crystal.

Furthermore, by stabilizing temperature and current of the pump source, the influence of the pump source temperature can nearly be eliminated. With a pump source developed by us we reached a current stability of ± 1μA and a temperature stability of ±0.0034°C inside the housing at a temperature change of ±1°C in the surrounding air.

4.2   TEMPERATURE COMPENSATION
The second way to reduce the temperature influence on the beat frequency signal is a mathematical compensation. For this purpose, we took the drift in the temperature T_{Air} of the surrounding air and T_{Sup} of the support as well as the drift of their temporal derivatives into account. We approximate the drift $\Delta f(t)$ of the beat frequency by the equation
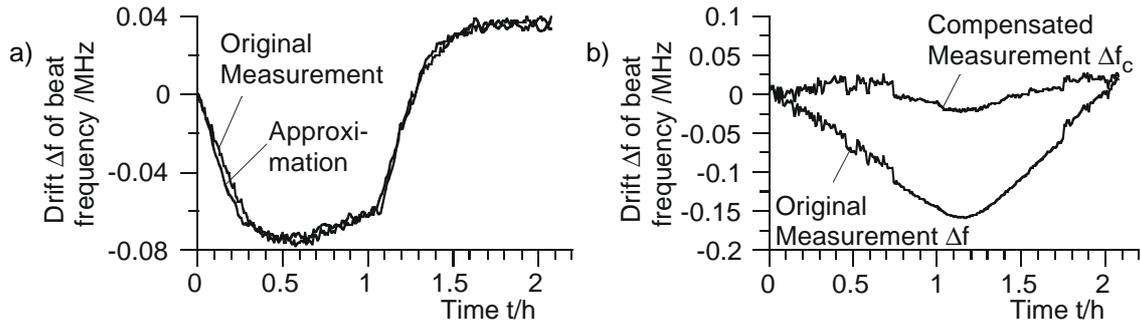
$$\Delta f * (t) = c_1 \cdot \Delta\left(\frac{dT_{Air}(t)}{dt}\right) + c_2 \cdot \Delta\left(\frac{dT_{Sup}(t)}{dt}\right) + c_3 \cdot \Delta T_{Air}(t) + c_4 \cdot \Delta T_{Sup}(t) \tag{5}$$

The quantities in Eq. (5) marked with Δ are the differences between their values at the time t and their values at t = 0.

Eq. (5) was used to approximate the drift of a measurement using the same crystal as in Fig. 4 and the temperature test signal 2. Using this test signal, more significant changes in the temporal derivatives of the temperatures occur. The constants $c_1...c_4$ were determined by the least square method. Fig. 6a shows the original measurement and the approximated curve. There are only small differences between original measurement and the approximation. Therefore, the drift Δf of the beat frequency can be predicted by means of measurements of the temperatures T_{Air} and T_{Sup}. The values of the constants $c_1...c_4$ are individual properties of the crystal and the configuration of the measurement setup. To show the usefulness of the approximation we applied Eq. (5) $c_1...c_4$ to compensate the drift of a measurement with the different temperature test signal 1 (Fig. 6b). We used the same crystal and the same values for $c_1...c_4$ as in Fig. 6a. The compensated drift $\Delta f_c(t)$ was calculated by

$$\Delta f_c(t) = \Delta f(t) - \Delta f*(t) . \tag{6}$$

By applying this dynamic approximation it is possible to diminish the temperature coefficient below 3 kHz/°C. The temperature behavior of the crystal is independent of the beat frequency f up to at least f = 200 MHz (see chapter 3.4). Taking into account the value f = 200 MHz for the beat frequency, a relative temperature coefficient $(df/dT_{Air})/f = 1.5 \cdot 10^{-5}$ /°C results. In the case of force measurements, [2] the value 3 kHz/°C corresponds to an apparent change in load of 0.1 mg/°C for crystals with the dimensions ø3 mm × 5 mm.

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Figure 6.   a)   Measured drift of the beat frequency f and approximation with Eq. (5) (temperature test signal 2),
            b)   Original measurement and compensated measurement of the beat frequency (same crystal and same values for $c_1...c_4$ as in Fig. 6a, but temperature test signal 1)

4.3   SINGLE-WAVELENGTH-MONOMODE OPERATION

In Fig. 3 the output power at 1064.1 nm is much greater than at 1061.5 nm. By reducing the pump power, the emission at 1061.5 nm is successfully suppressed. Oscillation of the fundamental transverse TEM_{00} mode at 1064.1 nm only enables the use of frequency counters or frequency-to-voltage converters to determine the beat frequency.

The number of oscillating longitudinal modes can be reduced by shortening the resonator length. The frequency difference between the TEM_{00} modes with the longitudinal orders q and q + 1 is the Free Spectral Range FSR. FSR depends reciprocally on the resonator length L. According to Eq. (1), for a resonator length L = 0.8 mm, FSR equals the spectral width of 100 GHz of Nd:YAG. For L   0.8 mm, with a linear resonator only a single longitudinal mode order can oscillate.

5   CONCLUSIONS

The beat frequency stability of monolithic, linear Nd:YAG lasers is sufficient for high-precision sensing applications. Without active frequency stabilization a relative temperature coefficient of f/f = 1.5 · 10^{-5} /°C should be achieved in the case of small-scale temperature variations of arbitrary time dependence.

The best frequency stabilities of Nd:YAG lasers are provided by nonplanar monolithic ring resonators. In these lasers, single-mode unidirectional operation can be achieved. Therefore a beat frequency f and a stability of f cannot be measured. However, with suitable pump powers more than one longitudinal mode oscillates. In this case, a beat signal with f = FSR is present. In [1] a temperature coefficient of dFSR/dT = -88 kHz/°C for FSR is measured. The value for FSR is 5.66 GHz. This leads to a relative temperature coefficient of (dFSR/dT)/FSR = $\Delta\nu/\nu$ = -1.5 · 10^{-5} /°C. This is exactly the same amount we achieved for the beat frequency stability f/f of the linear resonator. Therefore we conclude that the beat frequency stabilities of the non-actively-stabilized Nd:YAG lasers is comparable with the optical stabilities of free-running nonplanar ring lasers.

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