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Frequency stabilisation of twin orthogonal mode He-Ne laser

GERARD WYSOCKI*, KRZYSZTOF M. ABRAMSKI

Laser and Fibre Electronics Group, Institute of Telecommunications and Acoustics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

A double longitudinal mode He-Ne laser, without any polarisation elements inside its resonator, oscillates in two orthogonal linearly polarised modes. This two modes can be separated and their power difference easily detected can form error signal for frequency stabilisation of laser radiation.

1. Introduction

The simplicity of laser frequency stabilisation system is an important basic criterion of its applicability. There is a great demand for simple laser sources applied in optical metrology (interferometry, anemometry, vibrometry, velocimetry, *etc.*) with required long-term frequency stability on the level of $10^{-8}-10^{-9}$. There are a few techniques employed in laser frequency stabilisation [1]–[5]. The main idea of laser frequency stabilisation consists in single-mode operation controlled against a spectral reference feature such as a spectral absorption line, a saturated absorption element of the spectral line ("Lamb dip" or "absorption peak"), spectral line of the external Fabry–Perot etalon, *etc.* The basic technique of laser frequency stabilisation lies in frequency modulation of laser radiation (so-called dither) in order to obtain error signal by phase-sensitive detection technique. The main disadvantage of this method lies in extra frequency modulation caused by dither effect (its deviation is on the level of a few MHz), which drastically worsens short-term stability of the laser [6]. Although the long-term stability of such a laser can be extremely good (even better than 10^{-11}), dither effect causes that its applicability is strongly limited.

We present here a simple technique of frequency stabilisation applied to the commercially available He-Ne 632.8 nm laser with integrated mirrors and such a length of laser resonator which causes two-longitudinal-mode operation.

2. Twin-longitudinal-mode laser

A typical bandwidth of inhomogeneously (Doppler) broadened gain line of $3s_2-2p_4$ (632.8 nm) transition in He-Ne laser is about $\Delta\nu_D = 1.5$ GHz. In order to

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[*] Presently with the Johannes Kepler University, Linz, Austria.

obtain a single longitudinal mode operation, the cavity length of < 0.15 m should be applied according to the rule that the free spectral range (FSR) of the laser resonator should be larger than gain line bandwidth

$$\mathrm{FSR} = \frac{c}{2L} \geqslant \Delta\nu_{\mathrm{D}} \tag{1}$$

For longer resonator a He-Ne laser operates in more than one longitudinal mode. There is another interesting feature: namely, when the multimode laser operates without any polarisation selector (like a Brewster window), each mode is linearly polarised but neighbouring modes are polarised orthogonally. Because of the thermal effect, the "comb" of longitudinal modes of laser resonator sweeps in time. Often the additional effect, rotation in time of all linear modes (due to unequal heat distribution), is observed. In that sense the radiation from such a laser is called randomly polarised. However, when the length of the laser tube is thermally stabilised, the state of mode polarisation can be "frozen" and one can obtain a stationary set of orthogonally polarised modes. Particularly useful is the case of the laser with two orthogonal polarised longitudinal modes when such a twin-mode structure is frequency stabilised and the axes of polarisation are stable in space. It consists of two single-frequency beams $E_1(\nu_1,t)$, $E_2(\nu_2,t)$ separated in frequency with orthogonal mutual polarisation (Fig. 1). They can be written as follows:

$$\bar{E}_1(\nu_1,t) = \bar{\imath}_x E_{01}\exp[i2\pi(\nu_1 t + k_1 z + \varphi_1(t))], \tag{2}$$

$$\bar{E}_2(\nu_2,t) = \bar{\imath}_y E_{02}\exp[i2\pi(\nu_2 t + k_2 z + \varphi_2(t))], \tag{3}$$

with the basic condition FSR separation

$$\mathrm{FSR} = \nu_2 - \nu_1 = \frac{c}{2L}. \tag{4}$$

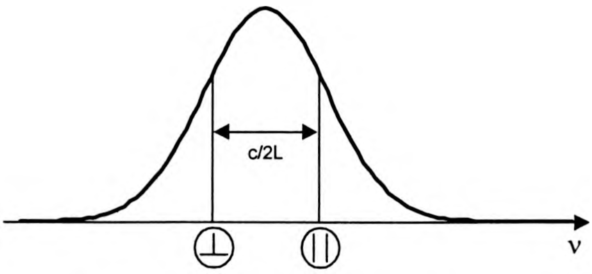

Fig. 1. Mode structure of twin-mode He-Ne laser.

When both orthogonal modes are set symmetrically to the centre of the Doppler broadened gain curve, both waves have the same power. This case has the following important features:

– keeping both modes symmetrically to the gain centre one can obtain efficient (no dither) frequency stabilisation,

– at the same time such a twin-mode laser is a perfect source of two linearly and orthogonally polarised beams.

This second property has a few advantages. A laser with two orthogonal modes naturally matches the axes of birefringent fibers and many other birefringent elements such as phase and amplitude modulators, giving new facilities of heterodyne interferometry [7], [8].

3. Experimental

The set-up of frequency stabilisation presented in this paper is shown in Fig. 2. The two-mode He-Ne 632.8 nm (Melles–Griot) laser with the length of the resonator $L = 170$ mm, the mode separation $\Delta\nu = c/2L = 890$ MHz, and with output power $P_{\mathrm{out}} \simeq 1$ mW was used as a source. In order to separate the main output beam from the probe beam, the probe beam (about 40 μW power) used to frequency stabilisation feedback loop was taken from the rear mirror of the laser, as is shown in Fig. 2. The beam from the rear mirror passes $\lambda/4$-waveplate in order to match the orthogonal axes of the polarising beam splitter. The orthogonal linear polarisations are spatially split. The error signal was formed in the detection block consisting of two balanced photodiodes measuring the power of each mode and a differential amplifier as a detector of mode power difference. The shape of discrimination characteristic, being the difference of mode powers versus laser frequency tuning, is presented in Fig. 3. The metal case of the laser was clamped into heat sink connected to the Peltier thermocooler (20 W element). Due to large thermal capacity of the laser case, the time characteristic of the system includes time delays. To

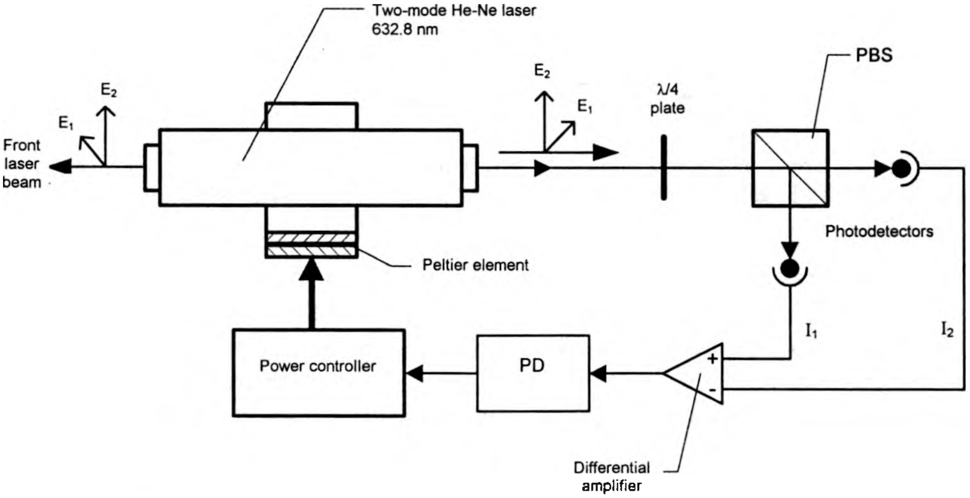

Fig. 2. Laser frequency stabilization set-up, PD – proportional derivative element, PBS – polarisation beam-splitter.

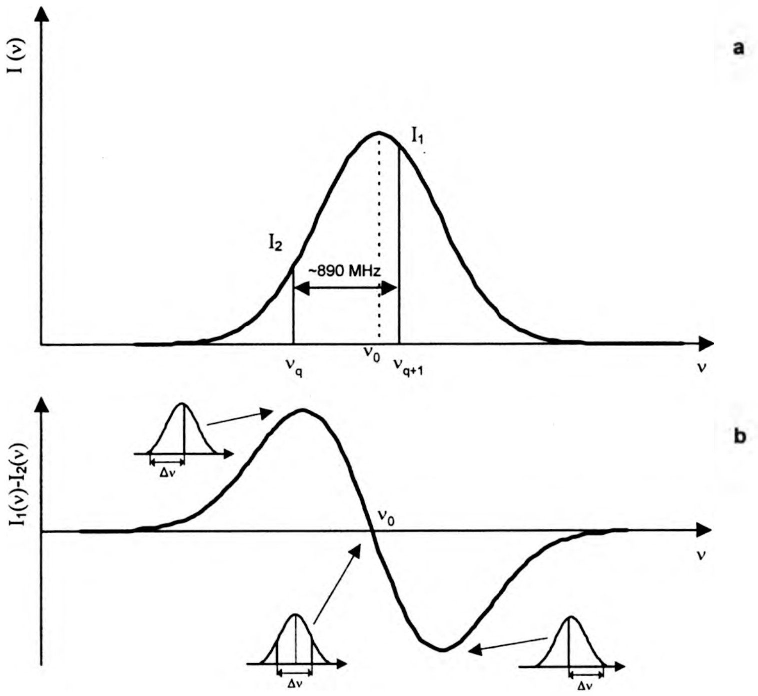

Fig. 3. Error signal formed on the basis of the difference of mode intensities, frequency axis shows position of modes relatively to the gain curve centre (a) and its discrimination characteristics being the difference of both mode power (b).

eliminate this effect of thermal inersion, the proportional derivative controller has been applied in the feedback loop. The error signal, correctly formed and amplified, controls the power supplied to the Peltier element, in such a way as to keep both modes of the laser symmetrical with respect to the gain centre. As a result, the effective frequency stabilisation was obtained without any losses of the main laser beam.

4. Frequency stability results

The frequency stability measurements have been performed in the classic heterodyne system (Fig. 4). As a reference source, the He-Ne/$^{127}I_2$ laser (produced by Polish company LASERTEX) was used. The highly stabilised He-Ne laser with iodine cell, operating at frequency corresponding to the "*j*" saturation absorption peak of iodine ($f = 473612236{,}270$ MHz) has been applied [9]. The results of the heterodyne frequency measurements (Allan Variance) have been registered by specially constructed Allan Variance counter [8], for two averaging times $\tau_1 = 1$ s and $\tau_2 = 10$ s (Fig. 5). The short term stability measurements have not been performed, because of the specific stabilisation method of the standard laser using frequency dither $f = 1.6$ kHz with a few MHz deviation. It is the "dither modulation" that worsens substantially the short term stability measurements. Two diagrams pres-

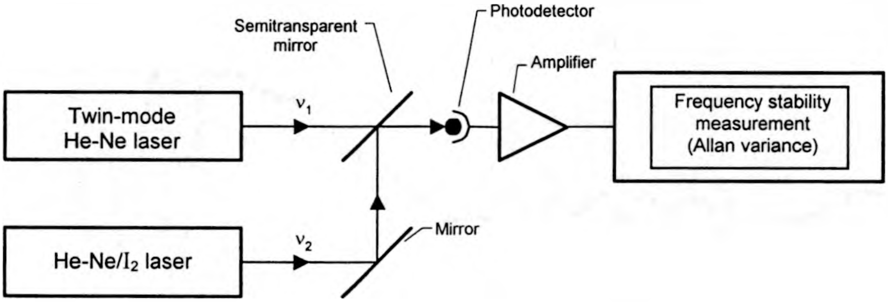

Fig. 4. Heterodyne system used for frequency stability measurements.

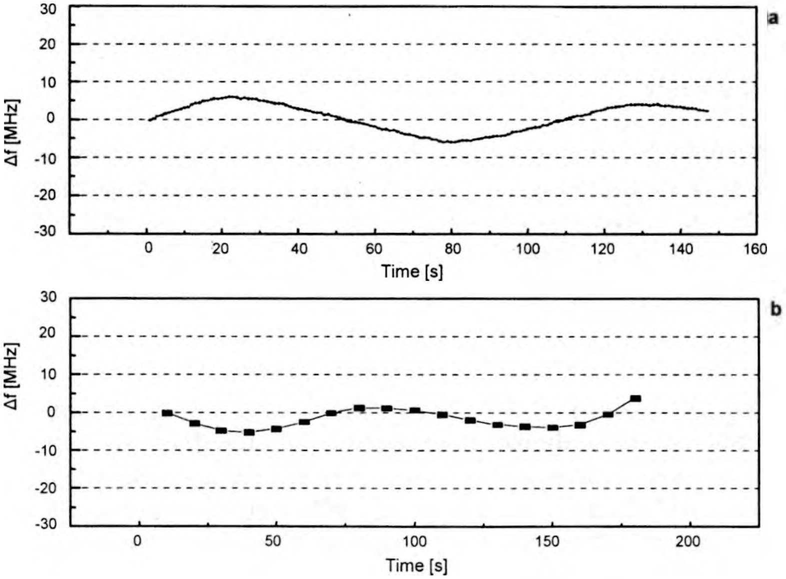

Fig. 5. Time courses of the laser heterodyne frequency: $\tau_1 = 1$ s (**a**), $\tau_2 = 10$ s (**b**).

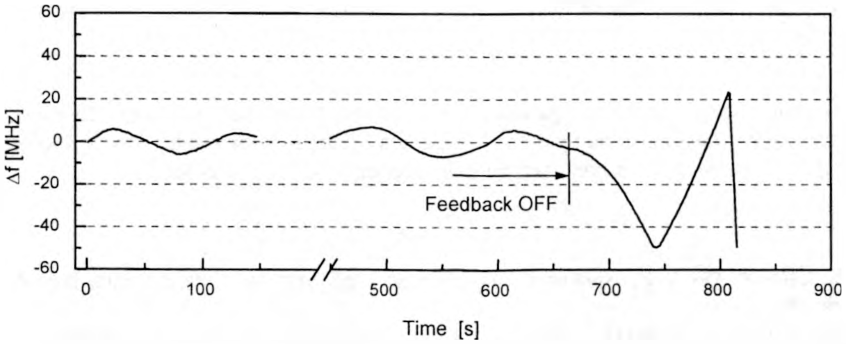

Fig. 6. Typical heterodyne frequency registered during stabilisation and after feedback OFF.

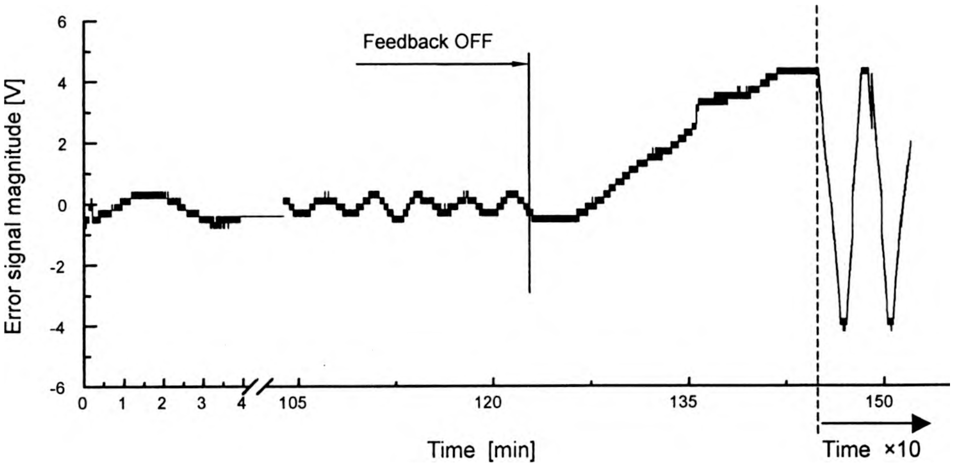

Fig. 7. Error signal registered during stabilisation and after feedback OFF.

enting frequency fluctuation and error signal behaviour for the conditions with stabilisation and without stabilisation are shown in Fig. 6 and Fig. 7, respectively. The frequency stability calculated on the basis of the Allan variance was $S(\tau_1) = 3.7 \cdot 10^{-10}$ and $S(\tau_2) = 3.1 \cdot 10^{-9}$, respectively, for two averaging times $\tau_1 = 1$ s and $\tau_2 = 10$ s.

5. Conclusions

The laser presented is a particularly useful source of two waves with two linear mutually orthogonal polarisations shifted in frequency on the level of several hundreds MHz (in our case it was 890 MHz). This source can be used in sophisticated experiments with heterodyne sensometry (fiber interferometry, vibrometry, anemometry, velocimetry, *etc.*), where one beam at frequency ν_1 operates as a stable reference beam and the second one operating at frequency ν_2 can be a measurement beam. Obtained results of the stability on the level 10^{-8} and better are good. It is enough for many experiments, where a few MHz low varying fluctuations of the laser are acceptable. The main advantage of this construction is its simplicity.

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