Properties and stabilisation of a short-resonator 543 nm HeNe laser

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Received 22 March 1995

Abstract

We report on the investigations of polarisation behaviour of a short-resonator internal-mirror 543 nm HeNe laser under axial and transversal magnetic field. An angular dependence of the polarisation properties on the orientation of the transversal field and Zeeman splitting under axial field is reported. The laser was then stabilised on the equilibrium of output powers in two orthogonally polarised modes and a stability within the range $3 \times 10^{-9}$ was achieved.

1. Introduction

The polarisation properties and behaviour of gas lasers have been widely investigated in theory and also experimentally. Many papers were published mainly about lasers emitting light on 633 nm line. The green line of 543 nm seems to be promising mainly in the field of two colour interferometry. Lasers using this transition in Ne have been produced only for a few recent years thanks to developments in technology and also only few papers were published in this field.

The majority of internal-mirror lasers tend to have two fixed orthogonal polarization planes with longitudinal modes polarised along one of these natural axes. Due to the intermode competition in a two- or a multimode regime the modes tend to be orthogonally polarised.

The green lasing transition shares the upper level with the red one: 3\$\Sigma_2^+$, while the lower level is 2\$\Pi_0^+$. The transition is of $j = 1 \rightarrow j = 1$ type. Lenstra \cite{1} predicts the same neutral behaviour in a single-mode regime as for the $1 \rightarrow 0$ transition if the quadrupole relaxations of populations are omitted. In a two-mode regime the result should be the same as in the $j \rightarrow j$ ($j > 1$) case i.e. two circularly polarised modes with the opposite or the same sense of rotation. Also the possibility of two ecliptically polarised modes with perpendicular main axes is mentioned there.

The Zeeman splitting of an $1 \rightarrow 1$ transition is presented in Fig. 1. Total angular momenta of both levels are 1 i.e. they consist of 3 distinct quantum levels each which are degenerate in energy in zero magnetic field. They are split by DC magnetic field into three energy levels labelled by $m = 0, 1, -1$. There are 7 allowed transitions among these levels with $\Delta m = 1, 0$ and $-1$. The Clebsch-Gordan coefficients of various transitions between Zeeman sublevels in the ground state and in the excited state of the $1 \rightarrow 1$ transition are in Fig. 2. The square of these coefficients give the transition probabilities of the corresponding transitions \cite{2,3}.

It can be seen that the probability of the transition $m = 0 \rightarrow m = 0$ is zero while the others are the same. The intensity of light emitted from each transition in conditions of a stimulated emission under a magnetic field is also influenced by other factors. The frequency...
Fig. 1. The Zeeman splitting of the $3s_2$ and $2p_{10}$ levels in Ne of the $1 \rightarrow 1$ 543 nm lasing transition.

and polarisation of an incident light and the inversion of population of the lasing levels.

The transitions with $\Delta m = 1$, or $-1$ will produce light with circular polarisation with respect to the magnetic field axis with opposite senses of circularity in both their spontaneous emission and their stimulated responses. These circularly polarised lines are called $\sigma^+$, $\sigma^-$. Linearly polarised transition with $\Delta m = 0$ is called $\pi$ transition [4].

In case of axial magnetic field the projection of the $\pi$ component in the direction of laser axis is zero so only the both circular $s$ components take part. In case of transversal field the $\pi$ component is linearly polarised, oriented along the magnetic field axis and both $\sigma$ components result in linear polarisation perpendicular to $\pi$ (Fig. 3).

The $g$ factors (gyromagnetic ratio of lasing levels) are for “red” transition nearly the same (they differ only five parts in thousand), thus the axial magnetic field causes a split into a gain doublet for the two allowed transitions ($\sigma^+$, $\sigma^-$) and a triplet in case of a transversal field ($\pi$, $\sigma^+$, $\sigma^-$). The “green” transition performs a more significant difference in $g$ factors (approx. 0.7), so the resulting structure is more complicated. Each sublevel is shifted in energy which results in a frequency shift of emitted light:

$$\Delta f = \frac{g \mu_0 B}{\hbar/(2\pi)}$$

where $\mu_0$ is the Bohr magneton, $B$ is the magnetic induction, and $\hbar$ is Planck’s constant. Each component of the transition has an associated Doppler velocity distribution. Zeeman splitting of the upper lasing level causes a frequency shift $\Delta f_1 = 18.2$ MHz/mT and the lower level $\Delta f_2 = 27.8$ MHz/mT. The intensity of the $\pi$ component in case of transversal magnetic field is larger by a factor of two [5,6]. The resulting inhomogeneously broadened lineshape is a superposition of contributions from all sublevels (Fig. 4).

The magnetically induced birefringence dominates in case of the red laser the end mirror birefringence even at low transversal magnetic field strengths and the components of dual polarisation are linearly polarised along the $\pi$ and $\sigma$ planes. A small difference in frequency (typ. 0–200 kHz) develops between these components. This difference varies as the mode is tuned through the gain profile due to the anomalous dispersion effect [7].

Each circularly polarised wave interacts primarily with its own component of the atomic doublet and experiences an index of refraction $n$ changed by the anomalous dispersion of its component of the doublet. For example the left circularly polarized wave experiences a resonant change in the index of refraction due to the higher frequency component of the atomic Zeeman doublet [8].

When the magnetic field is very small, these circularly polarised components are locked together in
phase so as to result in linearly polarised light. Only when the magnetic field is sufficiently strong the two components become unlocked. The components unlock only when there is a significant advantage in optical gain for the unlocked condition. At low fields the mirrors have a tendency to have a lower loss for one particular direction of linear polarisation which makes the components have a preference to remain locked together [9].

2. Magnetic field influence (experimental)

The Melles-Griot 05 LGR 025 543 nm HeNe laser with 732 MHz mode spacing was used. The influence of magnetic field was investigated by use of strong electromagnets. The electromagnet for generating of transversal field consisted of two coils wound around the sides of a plastic tube. The laser tube was placed inside without a mechanical contact with the electromagnet. Both coils had cores made of soft magnetic ferromagnetic material, so the maximum magnetic field intensity in the centre was 85 mT (=850 Gauss). This setup allowed an easy rotation of the field along the tube axis. The axial field was generated by a coil covering about two thirds of the laser tube. Both electromagnets were positioned near the anode.

The Fabry–Pérot scanning interferometer was used for observations of the mode behaviour. A non-polarising beam splitter was placed behind with two polarisers and two detectors. The rotation of these polarisers allowed detailed view on the mode polarisation. Amplified outputs from the detectors were put on vertical inputs of a two channel oscilloscope with a horizontal sweeping driven by a sawtooth signal that drove also the cavity length. The length changes of the laser were done by a heater made of a bifilarly wound flat wire around the laser tube near the cathode (Fig. 5).

2.1. Transversal magnetic field

The effects of transversal magnetic fields are much more sensitive to the orientation of the field than to its intensity. All modes have an elliptical polarisation which is nearly linear under the magnetic field oriented 45 degrees to fixed eigenpolarisations. The ellipticity slightly increases with rotation of the field and under high intensities of the field a tendency to circular polarisations was observed. The width of an instability

Fig. 4. Shifting of the Doppler-broadened lines associated with $\pi$ and $\sigma$ components.

Fig. 5. Experimental arrangement of the polarisation behaviour observations.
Fig. 6. The axial view of the laser with areas of transversal magnetic field orientation with different polarisation behaviour. They are symmetrical with respect to the natural polarisation planes of the laser.

Area "A" (no flipping)

This area is very narrow, about 5 degrees.

Under weak magnetic field of intensity up to approx. 55 mT the mode behaviour is regular, the laser works mainly in the two-mode regime and for a short tuning range in three-mode regime. The neighbouring modes have always an opposite polarisation. Under stronger magnetic field ranging from 55 mT up to 85 mT there is a preference for only one polarisation plane. The modes arise in it and vanish in it. There is also no flipping. The threshold of losses is now higher and a two-mode regime dominates accompanied by a very short single-mode regime (Fig. 7).

Area "B" (a single flip)

Fig. 7. Polarisation behaviour under transversal magnetic field oriented in area "A".

region depends not on the field intensity but only on its angle of rotation.

Areas of different behaviour are depicted in Fig. 6 in one quadrant but the same can be observed symmetrically in all four quadrants.

Area "A" (no flipping)

This area is very narrow, about 5 degrees.

Under weak magnetic field of intensity up to approx. 55 mT the mode behaviour is regular, the laser works mainly in the two-mode regime and for a short tuning range in three-mode regime. The neighbouring modes have always an opposite polarisation. Under stronger magnetic field ranging from 55 mT up to 85 mT there is a preference for only one polarisation plane. The modes arise in it and vanish in it. There is also no flipping. The threshold of losses is now higher and a two-mode regime dominates accompanied by a very short single-mode regime (Fig. 7).

Area "B" (a single flip)

Fig. 7. Polarisation behaviour under transversal magnetic field oriented in area "A".

It is broader than the previous one, approx. 10 degrees.

From weak field to 25 mT: two- or three-mode regime, there is one flip near the balance of powers of the two modes and all modes change their polarisation. With the increasing strength of the field the flip tends to move towards the moment of vanishing of one mode.

From 25 to 50 mT: also two- or three-mode regime, mode flipping when one mode vanishes. Also all modes change their polarisation.

From 50 to 65 mT: the modes arise in one polarisation plane and than quickly flip into the other plane. There is no more a three-mode regime.

From 65 to 85 mT: the same behaviour as under strong field in the previous area, all modes are in one polarisation plane.

All the threshold intensities are not precisely defined, they vary slightly with temperature and rotation of the field within the range of this area. With an increasing strength of the field the modes change from nearly linear polarisation to more elliptical. The flipping under stronger field is a slower process. The mode grows slowly to a circular polarisation and then flips at once into an elliptical one with a main axis rotated 90 degrees (Fig. 8).

Area "C" (with a region of flipping)

Also about 10 degrees.

The flip near the balance of powers of two modes is accompanied by oscillating.

The width of the region of oscillations is independent on the intensity of magnetic field. It changes only
when the magnetic field vector is rotated. This region broadens by rotation towards area “D”.

The frequency of oscillations varies by detuning from a few Hz on the edges of the instability region to approx. 10 kHz in its centre. The maximum frequency is independent on the magnetic field intensity and independent on its orientation.

The modes have elliptical polarisation, when the magnetic field intensity is increased over approx. 65 mT an increasing tendency towards circular polarisation can be observed. Under such conditions the oscillations are becoming less significant because the signal derived from a photodetector behind a polariser has a lower AC part.

Area “D” (instant flipping)
About 45 or 50 degrees wide.
All modes are instantly flipping from one polarisation to the other with the same frequency as in the instability region of area “C” (Fig. 9).

2.2. Axial magnetic field

The experiments with an axial field were performed with a huge electromagnet 90 mm long with 7200 turns of Cu wire able to produce a field up to 100 mT (=1000 Gauss).

There were also regions of instability observed. The dependence of oscillation frequency on the magnetic field intensity is much more significant compared to the transversal magnetic field. The tendency to circular polarisation under stronger fields seems to be similar to the transversal field.

The observations of mode behaviour under weak magnetic fields up to ca. 10 mT perform poor repeatability, there is an influence of the tube temperature. There is always at least one flip or a narrow region of instability. Also the elipticity of modes is varying.

Up to 5 mT: flip in the balance of powers in two mode regime, polarisation nearly linear.
From 5 to 7 mT: the mode arises in circular polarisation, than turns into nearly linear in the same plane as the other and in the line centre flips to the other. This flip is accompanied by a narrow region of oscillations corresponding with a single-mode regime. Later there is another flip but without oscillations.
From 7 to 40 mT: modes arise in one polarisation plane and than gradually flip into the other. It is accompanied by oscillations. The oscillations are the strongest in the line centre. There is mostly a two-mode regime and a narrow three-mode regime (Fig. 10).

With increasing of the magnetic field intensity the modes grow more and more circular so the oscillations are less significant. There is a clear dependence of the frequency and a portion of power influenced by the flipping (i.e. the AC part of an electric signal derived from a detector behind a polariser) on the field intensity (Fig. 11). The uncertainty of these frequency measurements is approx. ±0.7 kHz.

From 40 to 60 mT: at the magnetic field intensity of approx. 40 mT the AC signal caused by these oscillations vanishes in noise of the tube. The gain profile broadens with an increasing field intensity and two maximums can be observed. All modes have nearly
The frequency of the oscillations and AC part of the output power influenced by oscillations versus magnetic field.

circular polarisation. The two local maximums of the gain profile are unequal in both eigenpolarisations of the tube. Each of these maximums dominate in one of the polarisations. The width of the gain profile allows three- or four-mode regime. Modes arise in elliptical polarisation, tuned across the first maximum with the main axis in the dominant polarisation plane, than in the central minimum with a purely circular polarisation and finally elliptical again in the second maximum with the main axes in the other polarisation plane.

From 60 to 100 mT: the gain profile splitting is so wide that a gap between the two curves can be observed. There is an four- or (theoretically) five-mode regime but all five modes cannot be seen at once. One of them disappears in the gap. The two separate gain profiles are again unequal in size. One of them dominate in one polarisation plane and the other in second plane (Fig. 12).

2.3. Conclusion

The mode behaviour of this laser seems to be similar to previous reports with a quite unstable regime and even with regions of unsatbility and oscillations. The influence of magnetic fields was also previously investigated but not so generally [10,11] and the suppression of flips was reported. Only T. Lin [12] observed a beat frequency of 110 kHz under transversal magnetic field but independent on the field strength. The AC signals measured and observed with our laser are fast mode flipping with respect to their performance (as mentioned before). The way they arise from very low frequencies (even few Hz) having very strong and irregular frequency dependence to the detuning indicates the oscillations. The frequency dependence of intermode spacing due to the anomalous dispersion effects should be incomparably lower [13]. According to Rowley [9] the frequency splitting of a mode (the unlocking of the components) occurs only when there is enough optical gain for such an operation. It seems that in case of a very weak green transition the mirror anisotropy dominates and the splitting is than impossible. Even the red light emitting laser does not always perform this splitting under transversal magnetic field [5].

The predicted Doppler line splitting under the transversal field was not observed because the side $\sigma$ components are about half of size compared to the centre $\pi$ one. So the centre line dominates so strongly that the others are unable to rise above the level of losses.

Fig. 11. The frequency of the oscillations and AC part of the output power influenced by oscillations versus magnetic field.

Fig. 12. Polarisation behaviour under strong axial magnetic field.

Fig. 13. Stabilisation setup.
In case of the axial magnetic field there were two local maxima of the gain curve observed with a clear dependence of their spacing on the field strength as predicted.

3. Stabilisation design

Two rectangular-shaped permanent magnets were used for the polarisation behaviour control giving about 25 mT in the centre. They were oriented 45 degrees to the polarisation planes (area “A”) near the anode. So during tuning no flip occurs, the neighbouring modes have orthogonal linear polarisations and they stay in the same polarisation plane throughout the whole gain profile. The two polarisations are separated by a polarising beam splitter.

The laser tube is placed in a thick-wall aluminium tube housing. This should prevent any thermal influence of the outer atmosphere on the laser. High thermal conductivity of this housing will ensure very low thermal gradients that may cause bending of the tube and thus influence its performance. Also the circular cross-section of this housing seems to be more suitable for a self-contained coaxial laser tube with internal mirrors.

The stabilisation principle where the error signal is derived from the difference of powers in two orthogonally modes was used. This method was first reported in Ref. [14] and many 633 nm HeNe laser systems are now stabilised this way. The output from the rear mirror is practically undetectable so the part of the useful output power must be used for driving the stabilisation system. The two beamsplitters, two detectors and their amplifiers are positioned on a single holder in front of the tube (Fig. 13).

4. The stability measurement

The stability was investigated by measuring the beat frequency between the iodine-stabilised 633 nm laser and a 633 nm HeNe laser locked to the measured 543 nm one over a certain time period. The setup is depicted in Fig. 14.

The output light from the green stabilised laser is linearly polarised with a polarising beam splitter reflecting one of the polarised beams on a detector. Since the green laser works in two-mode regime with one mode separated by the beamsplitter the output light has a single frequency. Both the iodine-stabilised laser and the other red laser are in external-mirror configuration, so their outputs are also linearly polarised. Thus the light from the iodine-stabilised laser is totally reflected by the polarising beamsplitter to the avalanche photodiode. The discharge tube of the other laser is slightly rotated, so a portion of its output light passes through the beamsplitter and another part is reflected to the cavity.
The recording of the stability measurement over a time period about 20 minutes with an integration time 0.1 s is shown in Fig. 15. The standard deviation from the mean frequency is here 1.5 MHz. Because the resonance linewidth of the cavity for the red laser line is approx. five times smaller than for the green one the frequency fluctuations are caused by the instability of the green laser itself and by the instability of the locking of the Fabry–Pérot cavity to the green laser line. So it may be concluded now that the stability of the green laser is in the range $3 \times 10^{-9}$ or better.

References