XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

PROGRESS IN DUAL FREQUENCY HeNe LASER AND APPLICATION

S. Zhang, Y. Li and X. Zong
The State Key Lab of Precision Measurement Technology and Instruments
Department of Precision Instruments
Tsinghua University, Beijing, China

Abstract: Recent important progress in Dual frequency He-Ne lasers is reported, including two methods and experimental results to avoid mode competition and generate the frequency difference covering of 1~40 MHz, and the principle and the experiments of making a birefringence dual frequency laser itself be a displacement sensor with l/8 resolution, 8mm measurement range, and the function of self-calibration.
Keywords: Dual Frequency Laser, Displacement

1 INTRODUCTION

There are several He-Ne dual frequency lasers, which can be used in interferometers, such as longitudinal Zeeman He-Ne dual frequency lasers and transverse Zeeman He-Ne dual frequency lasers based on both Zeeman effect and mode pulling effect. While another birefringence He-Ne dual frequency lasers are based on frequency splitting technology.

If the frequency difference of a longitudinal Zeeman He-Ne dual frequency laser is larger than 3 MHz, the magnetic field is needed to be quite strong, which causes the frequency centers of the left and right rotation light separate almost 1500 MHz, the two gain profiles will part completely. This will make mode pulling of two frequency centers to a cavity mode impossible, and then there is no frequency difference from the lasers. The frequency difference of the transverse Zeeman He-Ne dual frequency lasers is even smaller; it is usually from tens of KHz to hundreds of KHz. Birefringence He-Ne dual frequency lasers can not output a frequency difference less than 40 MHz because too strong mode competition between the two frequencies makes one of the two modes die out. So there is a blank of frequency difference from 3 MHz to 40 MHz for He-Ne dual frequency lasers for long time.

From the viewpoint of applications of interferometers, the frequency difference of Zeeman He-Ne dual frequency lasers is small; it limits the max of the measuring speed to 700 mm/s. Now the movement speed of the numerical control machine tools has reached 1m/s. It is obvious that Zeeman He-Ne dual frequency lasers cannot meet this demand. While the frequency difference of birefringence He-Ne dual frequency lasers is large but the signal processing circuit at this frequency difference will be complex. Frequency difference ranging from 5 MHz to 20 MHz has long been expected in interferometers. Such a frequency difference is ideal for it not only allows high-speed measurement of interferometers used in checking machine tools, but also makes the signal processing much easier and cost much lower. In this paper, we will describe the principle and experiments of two kinds of He-Ne dual frequency lasers. They can fill up the blank of the frequency difference (from 3 MHz to 40 MHz) of Zeeman and birefringence He-Ne dual frequency lasers.

Furthermore we have made a dual frequency laser itself be a displacement sensor with nice characteristics. There are various methods for measurement of displacement, for example optical triangle sensors, laser interferometers, optical fiber linear frequency modulation sensors. We noticed the principle “When the cavity length changes half a wave length, the laser frequency will move one longitudinal interval”, which is similar to “When one arm of interferometer changes half a wave length, the stripe will move one level”. The latter has been widely used while the former was shelved for over 30 years. Combining frequency splitting technology with above principle, we utilize a He-Ne laser itself as the sensor with l/8 resolution, 8mm measurement range, and the function of self-calibration.

2 DUAL FREQUENCY LASERS

2.1 Principle of generation of 3~40 MHz frequency difference

We consider that birefringence dual frequency lasers cannot generate frequency difference less then 40 MHz because the ordinary light (o-light) and the extraordinary light (e-light) travel along the same path and interact with the same Ne atoms. The less the frequency difference is, the more intense the mode competition is. When the frequency difference is less than 40 MHz, strong mode competition makes one light die out, and the dual frequency laser will return to single frequency. The basic idea to avoid this is to eliminate the mode competition between the two frequencies. To achieve this, we should try to make the o-light and e-light interact with different Ne atoms.

According to the idea above, we have found two successful ways that one is to separate the o-light and e-light spatially, make them travel along different path and interact with the Ne atoms in their own paths, the other is to divide Ne atoms into two kinds by applying transverse magnetic field, one kind only interact with o-light and the other only with e-light.

2.2 Low frequency difference by separate the o-light and e-light spatially

The experimental setup is shown in figure 1. We have a full-external cavity He-Ne laser. M1 is concave with a radius of 1000 mm and coated with highly reflective layer. M2 is plane and used as the output mirror. T is the laser tube whose length is 260 mm. It ensures sufficient gain in spite of several optical surfaces in the laser cavity. The two window planes of the laser tube T are anti-reflectively coated. A 2.6 mm-thick calcite crystal C, which is anti-reflectively coated on both surfaces in 632.8 nm and cut at 45°, is placed between concave mirror M1 and laser tube T. A quartz crystal Q, which is also anti-reflectively coated on both surfaces in 632.8 nm and cut at 0°, is placed between laser tube

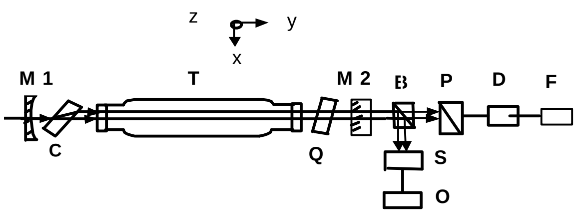

Figure 1. The scheme of low frequency difference by separate the o-light and e-light spatially

T and output mirror M2. Outside the laser cavity, B is a 50/50 beam splitter. It cuts the light beam of the laser into two parts: a reflective part and a transmitted part. The reflective part is received by a scanning-interferometer S, which transfers the light beam of the reflective part to the oscilloscope O, on which the oscillating modes can be seen. The transmitted part first passes through a polarizer P, which makes different modes coherent so as to form beats. Following the polarizer P is a photoelectric detector D, which can transform light into an electric signal then sent to a frequency meter F, which measures the frequency difference.

Calcite crystal is a kind of birefringence material like quartz crystal, but its birefringence is greater than that of quartz crystal. When a light beam passes through the calcite plate, it is spatially separated into two perpendicularly polarized eigenstates: ordinary light (o-light) and extraordinary light (e-light), then o-light and e-light will interact with different lasing medium in space, so the mode competition between the two lights decreases. Due to the restriction from the He-Ne laser bore diameter of about 1mm, the o-light beam and e-light beam cannot be completely separated in space, so the mode competition cannot be completely eliminated. We selected an appropriate spatial separation, which can not only ensure the gains of the o-light and e-light, but also decrease the mode competition of the o-light and e-light to a degree, which assures that the frequency difference can reach 3 MHz or so. The quartz crystal is used to tune the frequency difference between o-light and e-light. Since the birefringence of the quartz crystal is much weaker than that of calcite, quartz barely affects the spatial separation between o-light and e-light when the frequency difference is finely tuned.

The laser can always output frequency differences with minimum of about 3 MHz by tuning the angle between the laser beam and the crystalline axis of the calcite and the quartz crystal.

2.3 Zeeman-birefringence He-Ne dual frequency lasers

The experiment setup is shown in figure 2. It is a full inner cavity stress birefringence He-Ne dual frequency laser with 0.7 mW output power. M1 is a concave mirror with radius of 1 m; T is the laser

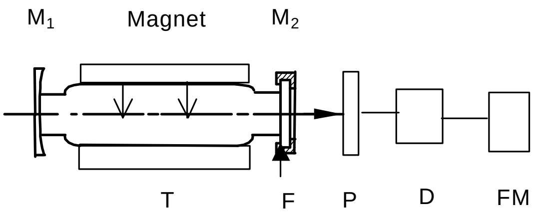

Figure 2. The scheme of Zeeman-birefringence dual frequency laser

tube whose length is 170 mm, the length of the capillary is 130 mm and the diameter of the capillary is 1 mm, the pressure in the tube is 0.3 torr. Along the tube, two magnets are placed symmetrically on the active medium of He-Ne laser to generate a transverse magnetic field. The length of the two magnets is as long as that of the He-Ne discharge tube. M2 is a plane output mirror, its inner side is anti-reflectively coated in 632.8 nm, and the outside is reflectively coated. A pair of force is applied on M2 along the diameter; P is the polarizer, which will make two orthogonal polarized lights coherent to form the beat. D is an optical electric detector; the coherent lights will be transferred here to electronic signal, then to frequency meter FM, which will show the beat frequency of the lights. The direction of the force F is parallel or perpendicular to that of the transverse magnetic field. The strained mirror M2 will generate artificial birefringence, then the laser will output two orthogonally polarized plane lights which we call o-light and e-light, and the polarization of the two lights are parallel or perpendicular to the direction of the magnetic field. The frequency difference is directly proportional to applied force:

$$\Delta n = \frac{8C}{pLDf_0} F \qquad (1)$$

Where **D***v* is the magnitude of split, C is the light velocity, L is the length of laser cavity, D is the diameter of the round plate made of optical glass, f_0 is the fringe value of the optical material and F is the force applied on the plate along a diameter.

The transverse magnetic field used in the experiment is 90 G or so. By tuning the force F we can conveniently and continuously tune the value of the frequency difference from 1 MHz to 40 MHz or even a few hundred MHz. One hour after the laser was turned on, let the length of the laser cavity vary in random in the open air, then we recorded the frequency difference (11 MHz) every 5 minutes. We can see the drift of the frequency difference is 0.1 MHz.

3 DISPLACEMENT SENSOR LASER

Laser frequency splitting technology makes it easier to study mode competition between the two frequencies, o-light and e-light. It has been proved that the power tuning or mode competition pattern of two frequencies is very interesting: spatially in one range of lasing bandwidth o-light just oscillates; but in another range e-light just oscillates if the cavity is tuned by moving a cavity mirror along the cavity axis; between the two there is a range in which o-light and e-light oscillate together. The bandwidth of each range changes with the magnitude of mode splitting. We can divide a longitudinal mode interval into four equal bandwidth ranges with different power tuning characteristics. When a cavity mirror is moved by a moving measured object, the displacement can be known from the output power variation of o-light and e-light out of the birefringence He-Ne laser. As $\lambda/2$ mirror displacement makes laser frequency moving one longitudinal mode interval, the accuracy of this method will be $\lambda/8$.

The experiment setup is shown in figure 3. We use a half inner cavity He-Ne laser. The window plate W of the laser discharge tube is made of K4 glass. A mechanical device is used to apply a tunable force F along a diameter of the window glass plate. A laser cavity mirror M2 can be moved along the laser axis. The tube is as short as 130 mm or shorter. The discharge current of the laser can be changed to vary the gain bandwidth. PS is a polarized prism.

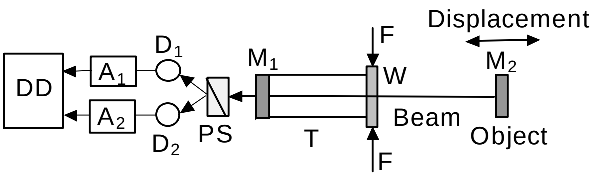

Figure 3. The scheme of making a dual frequency laser be displacement sensor

Let the laser cavity length is chosen as long as 140 mm, the laser longitudinal mode spacing will be 1070 MHz. It is well known that the laser lasing bandwidth will change with changing the discharge current of the He-Ne laser tube, which results from the dependence of the gain to the discharge current. We can get 800 MHz lasing bandwidth by providing appropriate current, and there will be no power output within the remaining 270 MHz of a longitudinal interval when the cavity length is tuned by moving the cavity mirror M2. It is easy to see that 270 MHz / 800 MHz is just the ratio of 1 to 3. In fact 1070 MHz is not only one of mode intervals that can be used. One can change both the longitudinal mode interval and lasing bandwidth, but keep the ratio of 1 to 3. Also, the lasing bandwidth can be changed by changing the cavity losses.

The next step is to tune the force applied on the laser window plate W. The laser longitudinal mode will be split into two components: o-light and e-light, due to the stress birefringence (photoelastic) of the plate.

In our case, equation (1) is approximately used because the neck of the laser tube bears some pressure from F. But the mode splitting must come into being and the relation is nearly linear between the frequency splitting and ambient pressure, which is proved by our experiments. In the case of frequency splitting, the beam from the laser is composed of two components that are of orthogonal polarizations. If the laser is mode-split and the laser cavity mirror (for example M2) is moved along the cavity axis, the two split frequencies will cross the lasing bandwidth. We see the phenomenon described by Fig. 4. Within the region from A to B there is o-light oscillation, at point B e-light comes into being so that there are two light components at to same time from B to C. At the point C, o-light extinguishes, only e-light is kept being until point D. The reason for only one light coming into being into regions of A to B and C to D is very strong mode competition between o-light and e-light, which leads one of them to die out. The width of three regions in lasing bandwidth would be changed if the mode split magnitude is changed. But the order is always kept: o-light region, intergrowth region of o-light and e-light, e-light region. The central frequency is located in the intergrowth region. If the magnitude of force is appropriate, the three regions will be equally wide.

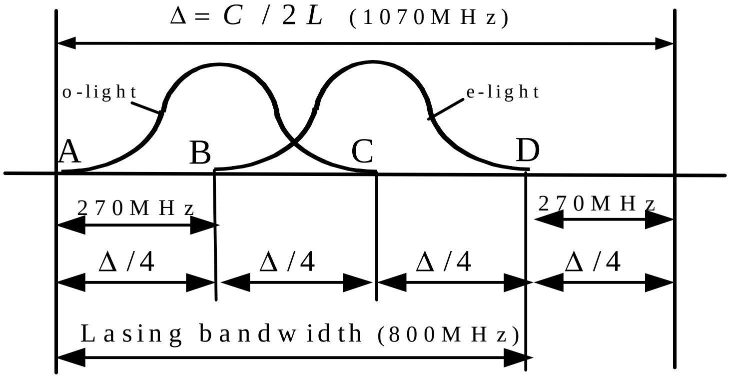

Figure 4. The power tuning curves of o-light and e-light of the dual frequency laser.

We will have four regions in one longitudinal mode spacing: o-light, both of o-light and e-light, e-light, no light. Thus we see in order D1 is lightened, D1 and D2 are brightened, D2 is brightened, neither D1 nor D2 is lightened.

Next, let’s see how long the displacement of the mirror M2 is if one frequency crosses one longitudinal mode interval.

As is well known, when cavity mirror M2 has a displacement ΔL, the frequency variation Δ*v* can be represented as

$$\Delta n = \frac{-n}{L}\Delta L \tag{2}$$

If Δ*v* =-*v*, i.e. the frequency moves one longitudinal mode interval, we have

$$\Delta L = \frac{1}{2}\, l \tag{3}$$

which has shown that the cavity length changes a half wavelength if frequency moves one longitudinal mode interval.

Such a fact associated with the technology of dividing one longitudinal mode into four parts has inspired us to study one new principle of measuring displacement. In the case of assuming the four regions described above to be spaced equally, the frequency will cross one of the four regions if the cavity length is changed by 1/8 wavelength. For 633 nm He-Ne laser beam, 1/8 wavelength means 0.078 μm. If the cavity mirror M2 is moved, the longitudinal modes will pass across the four regions one by one and the displacement of the mirror will be known by counting the number of the regions that the frequencies pass across.

Also, the direction of the displacement of the mirror can be distinguished by detecting different power characteristics of the four regions. Supposing the two frequencies (one o-light and one e-light) are in the B-C range right now where D1 and D2 are brightened at the same time. Their left movement will darken D2 and remain brightening D1. On the contrary their right movement will darken D1 and remain brightening D2. If the two frequencies are in the C-D range at the beginning where D1 is darken but D2 is brighten, their left movement will brighten D1 and D2 at the same time. On the contrary, their right movement will darken D1 and D2 at the same time.

4 CONCLUSION AND DISCUSSION

In order to weaken the intense mode competition between o-light and e-light, we have found two ways. One is to separate the o-light and e-light spatially so that the o-light and e-light can interact respectively with the Ne atoms. We introduce a calcite crystal into the He-Ne laser cavity. We also need a quartz crystal, whose birefringence is much weaker in comparison with that of the calcite, to finely tune the frequency difference from 3 MHz to 40 MHz. Due to the partially spatial separation in He-Ne laser, the mode competition still exists, so the minimum of the frequency difference cannot be less than 3 MHz. The other is to use transverse magnetic field about 90 G. The minimum of the frequency difference can reach 1 MHz, and the maximum is larger than 40 MHz or even to a few hundred MHz which has filled in the gaps between 3 MHz~40 MHz. So we can easily obtain an ideal frequency difference (5~20 MHz) that interferometers need.

The principle configuration of self-sensing displacement He-Ne lasers presented in this paper is simple. It looks like a single He-Ne laser but can measure displacement. It is an optical displacement sensor but without utilizing interference phenomenon or PSD elements or CCD. Besides, the method is not of principle non-linearity. The rule is that the frequency moves a longitudinal mode means a cavity mirror moving a half wavelength. This rule is not relative to the laser cavity length. The measurement range is large. If the length of the discharge tube is 139 mm, and in such case that 160mm cavity length is the longest to ensure the laser to output one pair of o-light and e-light in the cavity tuning, the measuring range is 30 mm.

This work is supported by the National Nature Science Foundation of China, State Science Technology Committee and Beijing Nature Science Foundation.

REFERENCES

[1] Sen Yang and Shulian Zhang, The frequency split phenomenon in a He-Ne laser with a rotational quartz plate in its cavity, Optics Communications, Vol. 68, (1988) 55-57.
[2] Yanmei Han and Shulian Zhang, Study of Hard-sealed, tunable, Photoelastic birefringence dual-frequency lasers, Chinese Journal of Lasers, Vol. B7, No.3, (1998).
[3] S.Zhang, K.Li, M.Wu and G.Jin, The pattern of mode competition between two frequencies produced by mode split technology with tuning of the cavity length, Optics Communications, Vol. 90, No.4, (1992) 279-282.
[4] Xin'an Guan, Dual frequency laser interferometers, Chinese metrology publisher, 1986.
[5] J.B.Ferguson and R.H.Morris, Single-mode collapse in 6328A He-Ne lasers, Applied Optics, Vol. 17, No. 18, (1978).
[6] Shulian Zhang, Minxian Wu and Guofan Jin, Birefringence tuning double frequency HeNe laser, Applied Optics, Vol. 29, (1990) 1265-1267.
[7] Yanmei Han, Shulian Zhang and Kelan Li, Extra-short He-Ne lasers based on mode splitting, Science in China (Series E), Vol. 39, No.2, (1996) 191-195.
[8] F.A.Jenkins and H.E.White, Fundamentals of optics, McGraw-Hill Kogakusha LTD, 1976, 646 p.
[9] W. Holzapfel and W. Settgast, Precise force measurement over decades applying the resonator-internal photoelastic effect, App. phys. B. Vol. 49, (1989) 69-72.

AUTHORS: S. ZHANG, Y. LI and X. ZONG, The State Key Lab of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing, China