Design of diode-pumped dual-frequency Nd:YAG green laser with large frequency difference for absolute-distance interferometry

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Abstract

A novel scheme of diode-pumped dual-frequency Nd:YAG green laser with large frequency difference is proposed in this paper. When a polarized beam splitter (PBS) is placed in resonant cavity of a diode-pumped intracavity KTP-frequency-doubled Nd:YAG green laser, a new birefringent filter consisting of PBS and KTP is formed (i.e., PBS-KTP) to select single longitudinal mode. A diode-pumped two-cavity dual-frequency green laser with a common medium of Nd:YAG has been designed, each resonant cavity of which is enforced to operate in single longitudinal mode by means of the birefringent filter of PBS-KTP. The frequency difference of the dual-frequency Nd:YAG laser at 532-nm can be tuned in a range of 0~360GHz, and its stability can be achieved approximately 10^{-6} by use of the Pound-Drever-Hall technique. Such a dual-frequency laser will be employed as an ideal light source of an absolute-distance interferometric system. The design principle is introduced briefly, the scheme and its feasibility of the dual-frequency laser are described and analyzed, respectively, and some preliminary results obtained experimentally are given.

Keywords: Nd:YAG laser, birefringent filter, dual-frequency laser, frequency difference, absolute-distance interferometry.

1. Introduction

It has been known that absolute-distance interferometry (ADI) is an effective way to precisely determine the dimensions of large-size workpieces. There are generally two kinds of ADI, one is a synthetic wave ADI, the other is a linearly frequency-modulated wave ADI, the former usually uses dual-frequency laser as light source, and the latter usually employs semiconductor laser diode as light source. In the circumstance of synthetic wave ADI, it requires that the frequency difference of dual-frequency laser source be as large as possible to get much shorter synthetic wavelength. This is because that for a limited phase measurement accuracy of coherent fringe, the shorter the synthetic wavelength, the higher the accuracy of the distance measurement. Therefore the research on dual-frequency laser with large frequency difference is of great significance for the synthetic wave ADI.

In recent years, various dual-frequency lasers have been investigated extensively, and the dual-frequency laser techniques have been developed rapidly [1]. Of the gas dual-frequency lasers, two-axial-mode He-Ne lasers are commonly employed. By controlling the discharging current of the gain tube of an all-intra-cavity He-Ne laser, Prof. Z F Zhou et al had obtained steadily simultaneous operation of two axial modes with a frequency difference of 600MHz~1GHz and a frequency-difference stability of 10^{-7} (in open air), such a stable two-frequency He-Ne laser had been successfully applied to ADI [2-4]. Using both Zeeman effect and laser longitudinal mode splitting phenomenon by intracavity birefringent element, Prof. S L Zhang et al had developed a number of orthogonally polarized dual-frequency He-Ne lasers [5], the frequency difference being turned from 1MHz to several hundreds of million-hertz, the stability of frequency difference being better than 2 \times 10^{-7}.
It has been noticed that the lasing bandwidths of solid-state lasers are much wider than those of gas lasers, thus it is possible for us to develop novel dual-frequency laser with very large frequency difference using solid-state gain medium such as Nd:YAG, Nd:YVO_{4}, etc. Based on the experimental study of the Nd:YAG laser longitudinal mode splitting phenomenon by an intracavity crystal quartz plate, Prof. M X Jiao had designed and demonstrated a diode-pumped birefringent dual-frequency Nd:YAG laser [6], the cavity of which contained a piece of crystal-quartz-made Fabry-Perot etalon acting as both a selector and a splitter of laser longitudinal modes, the frequency difference was approximately 2-GHz. By use of a twisted-mode cavity with fine detuning in diode-pumped Nd:YAG laser, a single axial mode was split into two orthogonally and linearly polarized modes, the frequency difference was able to be adjusted in the range from 10^{7} to 10^{9} hertz [7]. A single longitudinal mode of diode-pumped microchip Nd:YAG laser was also split into two modes by intracavity effect of photo-elasticity, and the frequency difference was tuned up to 3.4-GHz [8]. Both the photo-elasticity effect and the mode selection by the coupling cavities being applied, two-frequency simultaneous operation of a diode-pumped cw Nd:YAG laser had also been realized, the frequency difference between the adjacent orthogonally polarized modes could be varied from 50-MHz to 8.4-GHz [9]. A two-propagation-axis dual-frequency Nd:YAG laser system had been designed and established, the beat note from the two-frequency Nd:YAG laser was shown to vary from dc to 26-GHz [10]; A simplified version had also been built, the frequency difference was continuously tunable from zero to 10-GHz using the weak coupling between the laser eigenstates [11]. A diode-pumped stable two-axial-mode microchip Nd:YVO_{4} green laser system had been successfully developed [12]. The cavity was formed with a high reflectivity surface of the chip and an external mirror. The cavity length was set to 3-mm, and was automatically locked by using the Pound-Drever-Hall technique to suppress the thermal drift. The optical line width of each longitudinal mode was estimated to be about 100-kHz. The frequency difference of the two-axial-mode microchip Nd:YVO_{4} laser at 1064-nm was 50.5-GHz, and a frequency difference of 101-GHz of dual-frequency laser at 532-nm was obtained by extra-cavity frequency doubling.

It is obvious that the investigations of dual-frequency laser with large frequency difference have been focused on solid-state laser. In this paper, we present a novel scheme of diode-pumped dual-frequency Nd:YAG laser with a frequency-difference range of 0~360GHz and a frequency-difference stability of approximately 10^{-6}. The basic principle of design is briefly introduced in section 2, the scheme is described in section 3, the feasibility is analyzed in section 4, some preliminary results obtained experimentally are given in section 5, and a summary is included in section 6.

2. Principle of design

The dual-frequency laser designed in this paper is on the basis of principle of selecting single longitudinal mode by birefringent filter [13]. The filter consists of a polarizer (usually a Brewster plate, i.e., BP) and a birefringent crystal. The type-II phase-matched KTP is often used in the filter for nonlinear frequency transformation, therefore the BP and KTP elements form a birefringent filter, namely, BP-KTP. For a double pass through the KTP crystal, the phase difference between the ordinary and extra-ordinary rays is given by

$$\Delta \phi = \frac{4\pi \Delta n d}{\lambda}$$  \hspace{1cm} (1)

where \Delta n and d are the birefringence and geometric length of the KTP crystal, respectively, \lambda is the free-space wavelength of the fundamental beam. A beam that is polarized parallel to the high transmission axis of the BP will experience negligible reflection loss in a double pass through the BP-KTP filter provided that \Delta \phi is an integer multiple of 2 \pi. For other wavelengths at which the phase differences are not integer multiple of 2 \pi, the reflection losses from the BP can be significant. From equation (1) it follows that the free spectral range (FSR) of the BP-KTP filter, i.e., the frequency spacing between the adjacent filter transmission maxima, is given by

$$\text{FSR} = \frac{c}{2\Delta nd}$$  \hspace{1cm} (2)

When the FSR is larger than the gain bandwidth of the solid-state medium, the laser should oscillate in single longitudinal mode provided that the loss discrimination between adjacent longitudinal modes at the peak of the
filter transmission is adequate.

Up to now, a number of single-frequency solid-state lasers using the intracavity birefringent filter have been demonstrated and fabricated [14-16]. In order to achieve higher power single-frequency operation, multi-Brewster plates had been used in a diode-pumped intracavity KTP-frequency-doubled Nd:YVO₄ laser [17].

3. Scheme of dual-frequency laser

The scheme of our dual-frequency laser is schematically illustrated in Figure 1, which is a diode-pumped two-cavity dual-frequency green laser with a common gain medium of Nd:YAG. The high power fibre-coupled laser diode is temperature tuned by a thermoelectric cooler to the 808-nm absorption band of Nd:YAG crystal. The output light beam from the optical fibre core is imaged into the crystal using the specially designed optics. The pumping face (left side) of the Nd:YAG crystal is designed convex, and dielectrically film-coated for high transmission at 808-nm and high reflectivity at 1064-nm, the other face (right side) of the Nd:YAG crystal is anti-reflection film-coated at 1064-nm. OC₁ and OC₂ are two output couplers which are directly film-coated on the end faces of the type-II phase-matched crystals of KTP₁ and KTP₂, respectively, being high reflective at 1064-nm and anti-reflective at 532-nm. The other end faces of KTP₁ and KTP₂ are film-coated for anti-reflection at 1064-nm. Therefore two plane-concave cavities have been formed: one is composed of the pumping face of the Nd:YAG rod and OC₁ (called as straight cavity); the other consists of the pumping face of the Nd:YAG rod and OC₂ (called as square cavity). Both cavities have a common gain medium, and are related to each other through a block of intracavity polarized beam splitter (PBS) that acts as both a beam splitter and a polarizer. The intracavity PBS and KTP elements form a novel birefringent filter, namely, PBS-KTP. We see that the straight cavity contains a filter of PBS-KTP₁, and the square cavity includes a filter of PBS-KTP₂. The p and s components of the 1064-nm fundamental wave will simultaneously oscillate in single longitudinal mode in the straight and square cavities, respectively. Changing the direct voltage applied to the piezo-electric transducer (PZT) tube together with the transverse positions of both optical wedges of W₁ and W₂ inside the straight and square cavities, respectively, we can tune the resonant frequencies of single p-mode and s-mode within the Nd:YAG lasing bandwidth, and the p-mode and s-mode can obtain approximately equal gain coefficients. After frequency-doubled, the p-polarized and s-polarized 532-nm single-frequency laser beams can output from the straight and square cavities, respectively. Recombining the two single-frequency green laser beams by means of another polarized beam splitter (PBS₂), we can obtain a beam of orthogonally and linearly polarized dual-frequency laser at 532-nm.

It can be seen that the intracavity PBS is a very important element in the scheme. The transmission of p-component and the reflectivity of s-component should ideally be equal to 100%, but they are practically less than 100% on account of the imperfection caused during the course of PBS manufacturing. This will certainly result in a small portion of light in the cavities to escape from one face of the intracavity PBS component. The escaped beam is also orthogonally and linearly polarized dual-frequency laser at 1064-nm if the straight and square cavities oscillate simultaneously in single longitudinal mode. The p-polarized single-frequency laser at 1064-nm is extracted by a polarized beam splitter of PBS₂, and then input to a temperature-controlled Fabry-Perot cavity. The error signal of the servo system is fed back to a PZT tube attached indirectly to the Nd:YAG rod. The optical cavity-length of the straight cavity can therefore be locked using the Pound-Drever-Hall technique [18]. Once the p-polarized single-frequency laser is stabilized, the s-polarized single-frequency laser is simultaneously stabilized because of the symmetry of both cavities.

Figure 2 shows schematically the principle of the two-cavity dual-frequency Nd:YAG laser. By changing each cavity-length of the straight and square cavities, we can tune the frequency difference between the p-polarized 1064-nm single longitudinal mode and the s-polarized 1064-nm single longitudinal mode within the Nd:YAG lasing bandwidth of approximately 180-GHz. After frequency-doubled, the frequency difference of the 532-nm dual-frequency laser can be tuned from zero to 360-GHz.
4. Analyses of feasibility

In the scheme described above, we have employed the technique of birefringent filter to select single longitudinal mode, and a PBS element is used instead of the traditional BP element. It is known that a PBS element is equivalent to a pile of parallely placed BP elements. The theoretical and experimental investigations had indicated that more than one BP element placed parallely in a diode-pumped KTP-frequency-doubled laser cavity could effectively increase the selective loss of the birefringent filter to ensure single longitudinal mode operation in the condition of high pump power [17]. Thus the birefringent filter of PBS-KTP should have more powerful ability than the traditional filter of BP-KTP to select single longitudinal mode.

In order to further enhance the ability of single mode selection, it requires that the laser cavity-length be as short as possible. It had been shown that using a birefringent filter of BP-KTP, a 1064-nm single longitudinal mode operation had been achieved steadily when the Nd:YAG laser cavity-length was shorter than 100-mm [13]. In our scheme, if the Nd:YAG rod is 5-mm long, the intracavity PBS is made from K9 glass with sizes of 5mm × 5mm × 5mm, the two frequency-doubled crystals of KTP1 and KTP2 have the same sizes of 5mm × 5mm × 5mm, both optical wedges of W1 and W2 are 2-mm thick, then the optical path lengths of the straight and square cavities can be practically shorter than 50-mm, that is to say, a single longitudinal mode operation can be enforced easily in each cavity.

The experimental investigations had shown that using the Pound-Drever-Hall technique to stabilize laser frequency, a frequency stability of diode-pumped Nd:YVO4 laser at 532-nm had been better than 200-kHz [19] or even 100-kHz [12]. According to the experimental results, we can predict that it is possible to obtain a frequency-difference stability of approximately 10^-6 by means of the Pound-Drever-Hall technique in our scheme of the dual-frequency Nd:YAG laser at 532-nm.

5. Experimental results

In order to preliminarily verify the feasibility of the scheme designed above, we had established a diode-pumped two-cavity KTP-frequency-doubled Nd:YAG green laser system, each cavity of which contained a birefringent filter of PBS-KTP. When the optical lengths of both straight and square cavities were set to about 80-mm, and the laser-diode pump power incident on the pumping face of the Nd:YAG crystal was as much as 750-mW, simultaneous output of 532-nm green laser in both cavities had been achieved. The green output power from the straight and square cavities had been measured to be 1.3-mW and 1.8-mW, respectively. On account of the low output power, we had failed to observe the oscillating mode pattern of either straight cavity or square cavity by a scanning Fabry-Perot interferometer, using high power laser-diode as pump source can solve such a problem.

The polarization states had also been examined by use of an analyzer, it had been found that the two beams of green light output from the straight and square cavities were indeed orthogonally and linearly polarized, and the polarizing directions of both 532-nm and 1064-nm laser beams from the same cavity had been observed perpendicular to each other. In addition, we had observed that a small portion of laser at 1064-nm had indeed escaped from one face of the intracavity PBS element.

6. Summary

In this paper, the investigation progresses of the dual-frequency laser technology have been concisely reviewed; the principle of selecting single longitudinal mode by means of birefringent filter has been briefly introduced; a novel scheme of diode-pumped two-cavity dual-frequency green laser with a common medium of Nd:YAG has been proposed and analyzed, the frequency difference and its stability can be achieved up to 360-GHz and approximately 10^-6, respectively. The theoretical analyses and experimental results have indicated that the scheme of dual-frequency laser proposed in this paper is feasible.
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Figure captions

Figure 1. Schematic diagram of diode-pumped two-cavity dual-frequency Nd:YAG laser at 532-nm.
Figure 2. Principle of two-cavity dual-frequency laser with a common medium of Nd:YAG. (a) Nd:YAG gain curve, transmission curves of the birefringent filters of PBS-KTP1 (solid line) and PBS-KTP2 (dot line); (b) frequency combs of the straight and square cavities; and (c) oscillating two longitudinal modes.
Figure 1

Figure 2