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An experimental study and theoretical analysis of the mode characteristics of a narrow line-width, pulsed dye laser oscillator at different pump powers

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ABSTRACT

This paper presents an experimental study and theoretical analysis on the effect of pump power on the divergence, pointing, line-width and wavelength stability of a narrow line-width, high repetition rate dye laser oscillator. The dye laser oscillator, based on the hybrid multiple-prism grazing-incidence grating cavity, was pumped by copper vapor laser (CVL). The dye laser mode characteristics were studied at CVL average pump powers of 2, 4 and 8 W. The single pulse dye laser divergence/pointing stability was studied by far-field intensity distributions. The line-width and wavelength stability were studied using a high resolution wave-meter. The experimental results were theoretically analyzed in terms of dye laser mode structure drift induced by beam pointing instability, beam divergence and thermally induced optical path length fluctuation. A comprehensive theoretical treatment on pointing stability of dye laser beam and its influence in the dye laser wavelength stability is presented. The theoretical and experimental trends were found to be in good agreement.

1. Introduction

The beam divergence, pointing stability, line-width and wavelength stability are the mode characteristics of a dye laser oscillator. These cavity mode characteristics, defined as round-trip based self consistent solutions of circulating electromagnetic field in spatial, temporal and frequency domain, and their purity are related to the specifics of the dye oscillator optical resonator, optical quality of dye gain medium and external environment factors. These beam quality issues are particularly relevant in high flux pulsed dye laser pumping. In Ref. [1], in a pulsed dye laser, the mode structure fluctuation and frequency jitter have been measured and analyzed. The mode intensity fluctuation was attributed to pulse to pulse variation in the spontaneous emissions during the starting phase of the laser pulse [1]. The frequency jitter was attributed to a host of factors including mechanical vibrations of cavity components, turbulence and thermal effects in dye cell, pump beam fluctuations and intensity-dependent self-phase modulation effects [1]. In a related study, it was experimentally observed that the single dye laser pulse spectrum and mode intensities varied from pulse to pulse and all the axial modes did not build up simultaneously for most of the pulses [2]. Mode properties and misalignment sensitivity of dye laser resonators also presented a diverging behavior in different stability zones [3]. The issues are even more serious in high repetition rate pulsed dye laser such as with copper vapor laser (CVL)/2nd harmonic of Nd:YAG pump sources. Due to high repetition rate, the fraction of absorbed pump radiation leads to heating of the dye solution. This is true even if the dye solution is suitably flowed pass the pump beam [4]. The resulting dye gain medium, therefore, is inhomogeneous [5,6]. The ambient temperature fluctuation and residual heat absorption in the cavity components also lead to dye gain medium thermal instability [7]. The temperature gradient caused by non-uniform heating of the dye solution was studied [5]. The fluctuation of pump beam intensity induces differential heating of dye solution during different pulses. The non-uniform changes in the refractive index gradient of the dye solution lead to the dye laser beam deflection differently during different pulses and therefore instability in the cavity modes. The possible misalignment errors were due to transverse beam displacement, angular beam displacement, longitudinal waist displacement and waist size mismatch of a source laser with respect to a reference cavity [8]. The frequency shifts/stability associated with angular changes of a beam injected into a reference cavity was studied [9]. The pulse to pulse misalignment effects give rise to both angular drifting of output laser pulse from the reference axis and drifting of resonant frequency from the reference cavity. The change in transverse profile of the wave front also leads to change in mode frequency. It is well known that off axis modes and side modes have slightly different frequency [10]. The dye solution temperature and gain medium flow affect the line-width and wavelength stability of a single

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mode dye laser pumped by copper vapor laser [11,12]. Environmental wave front distorting *factors* such as mirror misalignment due to thermal acoustic noise and refractive index inhomogeneity in the cavity affect *the* resonator mode. The gain medium width depends on pump beam quality and it varies even within a pulse [13]. The change in gain medium size due to pump beam intensity, divergence and pointing fluctuation may change the size of beam waist of different pulses. Laser pointing stability is affected by the thermally heated gain medium which introduces wedge, thermal lensing that cause wave front distortion [14]. The stimulated emission starts from spontaneous emission (noise) which is random in phase and amplitude distribution across the gain medium. Due to random nature, the starting optical seed is also different from pulse to pulse which affects the laser axis affecting laser pointing stability [14]. Various factors that affect pointing stability also affect spectral stability of the dye laser. It is understandable that in most of the applications of pulse dye laser as an oscillator or in MOPA configuration, such as selective excitation of isotopes, phase matching based non-linear frequency conversion and Raman processes, the stable dye oscillator output in terms of frequency, line-width, divergence and pointing will play a crucial role. The motivation of this paper is to study, both experimentally and theoretically, the stability issues of pulsed dye laser at different pump powers.

This paper focuses on a comprehensive study on the mode characteristics of a narrow line-width ($\approx$ a few GHz) dye laser in terms of beam divergence, beam pointing, line-width and wavelength stability at different dye medium head load. The dye medium heat load is changed by utilizing three different copper vapor laser (CVL, 5.5 kHz) pump powers of 2, 4 and 8 W. The dye laser oscillator was based on the hybrid multiple-prism grazing-incidence (HMPGI) grating optical resonator. The experimental trends in dye laser beam divergence and pointing angle were studied by recording far-field intensity distribution over 500 single pulses, each with separation of about 1 s. The dye laser line-width and wavelength stability, over a period of several minutes, were studied with a high-resolution wave-meter. The experimental results were theoretically analyzed in terms of dye laser mode structure drift induced by beam pointing instability, beam divergence and thermally induced optical path length fluctuation. A comprehensive theoretical treatment on the pointing stability of dye laser beam and its influence in the dye laser wavelength stability is presented. Geometrical analysis of the effect of the single pulse intra-cavity beam tilting on the central wavelength fluctuation of the dye laser with/without prism beam expander was carried out. Single pulse intra-cavity beam tilting is attributed to beam pointing instability of the laser output. The change in laser axis leads to change in the angle of incident on the grating and which in turn induces dynamic line-width and mode structure instabilities. The theoretical and experimental results were found to be in good agreement. To the best of our knowledge, such comprehensive/unified treatment of the subject is not available in reported literature.

2. Experimental setup

Fig. 1 shows the schematic of the experimental setup of a CVL pumped dye laser to measure the single pulses dye laser mode characteristics, i.e. pointing stability, divergence and line-width and wavelength stability. A confocal positive branch unstable resonator (PBUR, $M=12.5$) loaded CVL oscillator (repetition rate $\sim$5.5 KHz) is used to pump the dye laser [14]. Both CVL and CVL pumped dye laser are homemade. A specially designed circular stainless steel (SS) dye cell was used in the present experiment, as reported in Ref. [15], where dye cell and all the optical components are integrated in a heavy SS architecture to reduce the effect of mechanical vibration. The CVL beam pumped the dye laser, focused by a cylindrical lens (L_1) of focal length 50 mm. Laser grade Rhodamine-6 G dye in the ethanol (1 mM) was circulated in dye cell at flow rate of about 1.75 l/min. The dye solution flow rate was measured by a flow meter (turbine type, Electronet Equipment, FL-100). The flow rate of the dye solution was controlled by variable frequency drive (VFD) controlling the dye circulation pump. The dye circulation system incorporated a thermoelectric cooling (TEC) based heat exchanger to maintain dye temperature $24 \pm 0.1\,^{\circ}$C [11]. The dye oscillator resonator consisted of a broadband tuning mirror (M_3), a grating (2400 lines/mm) in grazing-incidence, a double (P_1 & P_2) prism beam expander (magnification $\approx$ 22), a dye cell and a partially reflecting output coupler (M_2). The prism pair folds the incident dye beam about 90° with respect to dye cell and also provide the beam expansion. The angle of incidence on the grating is $\approx$ 80°. The broad band tuning mirror is rotated about an axis perpendicular to the plane of incidence to tune the dye laser. The overall cavity length was 17 cm. The first order diffracted beam was fed back into dye gain medium by a broad band reflecting mirror. The dye laser beam was taken out through the transmission of output coupler (reflectivity $\sim$40%). To measure the dye laser mode properties (divergence and pointing instability), a part of dye laser beam was focused by a lens L_2 (focal length = 25 cm) placed at a distance of 35 cm from the dye laser output coupler. The lens focused the dye laser output beam at a distance of $\sim$50 cm. This far-field spot was re-imaged in magnified mode by another lens L_3 (f = 25 cm). An aperture, A, was placed at minimum spot size to remove the amplified spontaneous emission (ASE). The spatial profile at the far-field spot of lens L_3 is the magnified (12.5 times) image of the far-field pattern at the focal spot (location A) of lens L_2. The magnified far-field pattern was recorded with the help of a visible 12-bit CCD camera (Model No. – Pixelfly qe from PCO AG, Germany) of pixel size 6.45 μm and analyzed by in-house developed software [16]. Suitable combination of ND filters was used to attenuate the beam intensity to below saturation of CCD. The beam divergence was estimated from the width of the far-field intensity distribution at $1/e^2$. The pointing stability of different pulses of the laser beam is determined by the displacement of the intensity peak from their modal position. The detail procedure of beam pointing stability measurement is discussed elsewhere [14]. The horizontal and vertical pixel positions of the intensity peak for each pulse are determined by the software, which provides information about drifted position of the peak. The dye oscillator wavelength/line-width and their stabilities were studied by the wave-meter (WS-7, Angstrom, High finesse) at the rate of 30 Hz in pulsed mode [11,17]. Laser radiation was guided into wave-meter through the optical fiber. The wave-meter is used to study laser wavelength variation. However, with additional features, this commercial instrument [18] also measures laser line-width behavior. All the spatial and spectral dye laser data were collected for the CVL pump powers of 2, 4 and 8 W. These pump CVL powers were varied externally by a set of partial reflectors (M_1) without any change in electrical input parameters.

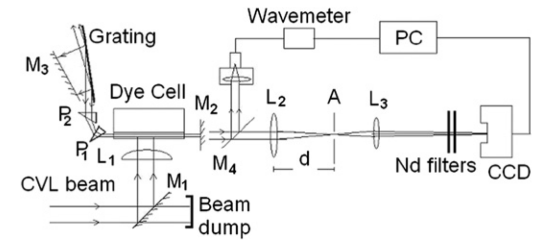

Fig. 1. Experimental set-up for measuring dye laser pointing, divergence, wavelength and line-width stability.