All-optical tunability of holographically multiplexed organic distributed feedback lasers

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Abstract: We report the fabrication and characterization of optically pumped multiple grating distributed feedback lasers in dye doped organic thin films. Each multiplexed laser structure is inscribed at a different angle in the sample plane and possesses a unique emission wavelength. The polarization sensitivity of these structures with respect to the pumping light is exploited to enable simple and high-speed switching of the device emission wavelength.

OCIS codes: (140.3490) Lasers; distributed-feedback; (250.3680) Light-emitting polymers; (160.3380) Laser materials; (160.4890) Organic materials

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1. Introduction

Organic materials have emerged as promising alternatives for a variety of devices which are traditionally fabricated from inorganic materials or semiconductors. Techniques such as photolithography, [1] ink jet printing, [2] and micro-molding, [3] can be used to prepare low cost and lightweight devices from organic materials on flat, curved, [4] or even bendable [3,5] substrates. Additional advantages exist for lasers based on organic materials, such as lower self-absorption and weak temperature dependence of the laser characteristics, including the emission wavelength and laser threshold [6,7]. Although electrically pumped amorphous organic lasers have yet to be realized, applications are still possible with optical pumping using low cost microchip lasers as pumping sources [8-11].

Distributed feedback (DFB) type resonators are widely employed for organic lasers due to their simple and low cost fabrication and their easily observed laser characteristics. Among the attractive features of DFB lasers is the possibility to couple the emitted radiation out of the sample perpendicularly to its surface. This can be achieved by creating refractive index gratings that use second order of diffraction for resonator action ($m = 2$, *vide infra*), in which case first order diffracted light is coupled normal to the surface [12]. Another important aspect of DFB structures is that the grating period (Λ) of the periodic index or gain pattern sets the laser emission wavelength following the relation $l_L = 2\Lambda n_{eff} / m$ where n_{eff} is the effective refractive index of the guided mode responsible for lasing and m is the order of diffraction responsible for the feedback. Thus, the laser emission wavelength may be tuned within the gain spectrum of the medium (typically ~40 nm) by altering either Λ or n_{eff}, while the gain spectrum can be displaced throughout the visible and near infrared with the use of different laser dyes [13].

The grating period is determined either during the fabrication process (lithography, printing, molding) or by the pumping configuration in the case of transient gratings [8,13]. Indeed, the latter requires mechanical rotation of the sample, which adds cost, complexity and volume to the device, and precludes high speed tuning of the output wavelength. Varying the thickness of the DFB film changes the effective refractive index with fixed Λ and allows wavelength tunability, however this requires the use of multiple samples [9,14]. Another possibility is thermal induced modification of the refractive index, but large temperature changes are required to tune over a very limited spectral range [6]. Recently much more promising approaches to tuning of the emission wavelength have been demonstrated, including modification of Λ using the mechanical stress on elastomeric polymers, [5,15] and modification of n_{eff} through the application of external electric fields to liquid crystal based wave guide lasers [16,17]. In this work, we demonstrate the multiplexing of several dye doped DFB resonators in order to obtain a single device with several laser emission wavelengths which can be chosen during sample fabrication to be anywhere within the gain spectrum of the dye employed. Moreover, it is shown that the polarization sensitivity of such lasing structure

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allows the optical switching of the emission wavelength by varying the polarization of the pumping light.

2. Multiplexing DFB gratings

The organic DFB lasers presented here were based on the UV sensitive polymer poly(styrene-*co*-4-vinylbenzyl thiocyanate) (PST-*co*-VBT) doped with 2% wt. of the laser dye DCM (4-dicyanmethylene-2-methyl-6-4H-pyran, from Radiant Dyes). A periodic change of the refractive index was created by interference patterning using overlapping beams from the fourth harmonic of a 10 Hz Nd:YAG laser (Spectra Physik / Quanta Ray-GCR 170-10) at l = 266 nm. The angle q between the two beams was used to select the grating period Λ, according to the relation $\Lambda = l / 2 \sin q$, where l is the irradiation wavelength. To inscribe multiple gratings, the UV illumination was carried out n (n = 2-4) times using a different grating period for each exposure, with the sample being rotated by 180/n degrees between each illumination. The inscribed gratings can be further modified with reactive gas-phase chemical treatment with amines (e.g., ammonia) which results in an additional index change accompanied by the formation of a surface relief grating [5,18]. An atomic force microscope (AFM) image (Nano Scope® IIIa and Dimension 3100, Digital Instruments, tapping mode) of an organic thin film having three index and surface relief gratings (modulation depth of ~40 nm) written at angular intervals of $60°$ (n = 3) is presented in Fig. 1. The corresponding grating periods are Λ = 398, 409 and 419 nm, and the sample thickness is ~420 nm as measured by spectroscopic ellipsometry (Woollam VASE spectroscopic ellipsometer).

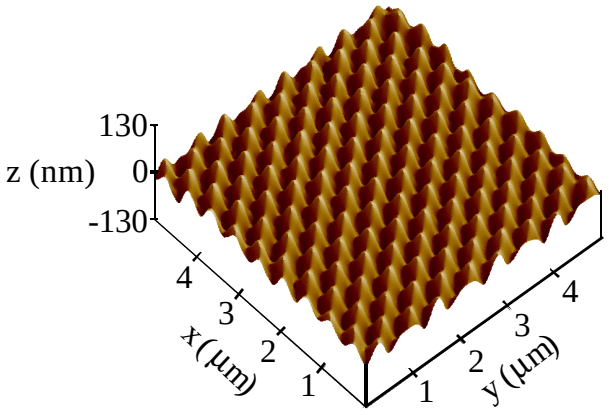

Fig. 1. AFM surface profile of DFB laser sample with three multiplexed gratings. The grating modulation depth is ~40 nm.

3. Optical characterization

3.1 Experimental set-up

Figure 2(a) is a schematic of the experimental configuration used to characterize the basic lasing characteristics of the samples presented in this work. A doubled Nd:YAG laser was used as the pumping source, producing ~20 ps pulses at 10 Hz and 532 nm. Samples were pumped at normal incidence with a spot of ~600 μm radius (measured with a knife blade technique). Light from the flash lamps and other harmonics of the pump laser were removed with a pass band filter placed before the sample. A half wave plate/polarizer combination was used as a variable attenuator, which also ensures that the excitation light is linearly polarized. A half wave plate placed just before the sample was used to control the polarization direction

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of the pump beam, characterized by the angle a between the electric field $\mathbf{E}_p$ and the x-axis (Fig. 2(b)).

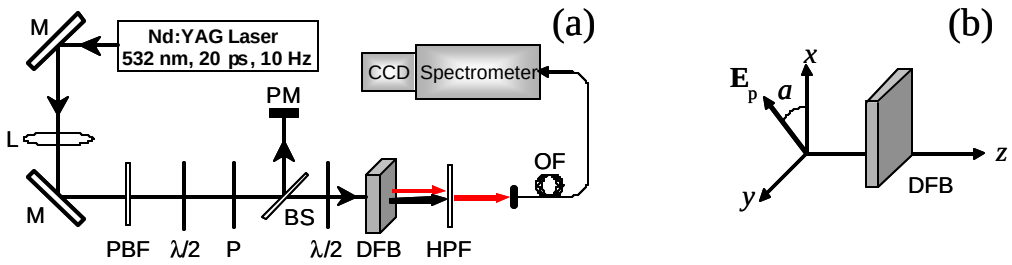

Fig. 2. (a) Experimental apparatus. M: mirror, L: lens, PBF: pass band filter, P: polarizer, BS: beam splitter, λ/2: half wave plate, DFB: distributed feedback laser sample, HPF: high pass filter, OF: optical fiber, PM : Power Meter (b) Orientation of the pump polarization direction impinging on the sample where a is the angle between the pump electric field $\mathbf{E}_p$ and the x-axis.

Several percent of the pump beam was diverted to a power meter (PD-10 Ophir) by a glass plate to measure the pump beam power. The transmitted pump light was blocked by high pass filters, while light from the DFB lasers was collected into a fiber bundle of ~1 mm diameter, by which it was directed into a spectrograph (model MS125, Oriel Instruments), which dispersed the emission onto a cooled CCD camera (Andor Technologies).

3.2 Typical laser characteristics

A typical plot of the emission intensity vs. pump intensity for a typical single grating DFB laser in our material is shown in the Fig. 3(a) when the pump beam is linearly polarized with $\mathbf{E}_p$ perpendicular to the grating wave vector $\mathbf{K}$. Three distinct regimes are observed as the pump intensity is increased: fluorescence at low intensities (a), followed by a steep increase of the emitted intensity at the onset of laser action (b), and finally saturation at higher intensities (c). When operating in the saturation region the emission is sufficiently intense to be measured with a standard power meter such as the one mentioned above. This characteristic curve will hereafter be referred to as the "input/output curve".

A plot of the actual output power vs. the absorbed pump power (sample OD at 532nm ≈ 0.05) is given in Fig. 3(b). A linear fit in the saturation region yields a slope of 0.027, corresponding to a conversion efficiency near 3% which is typical for optically pumped solid state lasers. The width of the emission peak is below our experimental resolution limit of ~1 nm and is highly polarized (>250:1) parallel to the grating planes of the sample, regardless of the pump polarization.

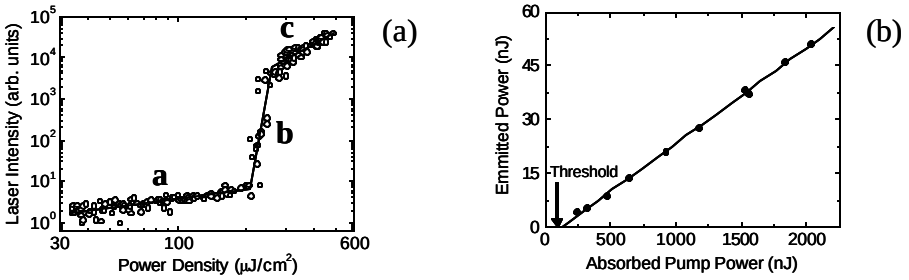

Fig. 3. (a) The laser emission intensity plotted against the pump intensity, where the lines are power law fits for each of the region referred as (a), (b) and (c) (see text for details). (b) Emitted laser power plotted against the absorbed pump power, the solid line being a linear fit with slope 0.027.

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However, the optical pumping is most efficient when $\mathbf{E}_p$ is perpendicular to $\mathbf{K}$, since in that case the maximum amount of fluorescence is directed into the resonator axis (the direction of $\mathbf{K}$).[14] Detuning the pump polarization angle from its optimal position results in a decrease of the emission intensity until the sample eventually no longer lazes. The spread of angles for which lasing occurs will depend on the pump intensity and the distribution of fluorophores in the thin film [14].

3.3 Multiplexed DFB properties

Described below is a sample having three gratings with corresponding wave vectors $\mathbf{K}_{30°}$, $\mathbf{K}_{90°}$ and $\mathbf{K}_{150°}$ making angles of 30°, 90°, and 150° respectively with the *x*-axis. Figure 4 presents the normalized emission spectra obtained by pumping the sample with a = 120° (open squares), a = 60° (stars) and a = 0° (filled triangles), the three angles for which lasing is optimal for each grating. We observe laser emission at 630.6, 635.0 and 638.7 nm which corresponds to the grating wave vectors $\mathbf{K}_{30°}$, $\mathbf{K}_{150°}$ and $\mathbf{K}_{90°}$ respectively.

However, for most values of a the emitted signal contains more than one of these wavelengths as shown in Fig. 5, which displays the emission intensity with respect to the pump polarization direction a at a fixed input intensity of 8.5 mJ/cm^2. We observe three lobes, each of them corresponding to a given grating (see symbols), which can be fitted by considering the evolution of the intensity directed into the resonator axis (solid lines) following a procedure presented in detail in reference [14]. Qualitatively, detuning the pump polarization from the optimal angle for a particular grating causes the laser to descend regions (c) and (b) of its input/output curve. Consequently, the angular spread of these lobes is strongly dependent on the pump beam intensity, and increases with increasing intensity since more of the laser input/output curve is traversed before dropping below the laser threshold. The change in curvature in each lobe represents the transition between regions (c) and (b).

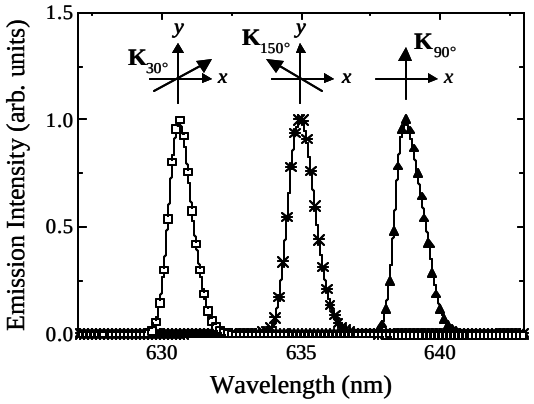

Fig. 4. Normalized emission spectra of a DFB laser structure having three multiplexed gratings, obtained by varying the pump polarization direction a. Open squares: peak at 630.6 nm (a = 120°), stars: 635.0 nm (a = 60°), filled triangles: 638.7 nm (a = 0°), the corresponding wave vectors $\mathbf{K}_{30°}$, $\mathbf{K}_{150°}$ and $\mathbf{K}_{90°}$ make angles of 30°, 150°, and 90° respectively with the *x*-axis.

The narrower lobe observed for the peak at 638.7 nm (filled triangles) is a sign that this grating has a higher lasing threshold, closer to the incident intensity. Indeed, the fitting procedure yields 5.8 mJ/cm^2 for the threshold of this grating as opposed to 4.8 mJ/cm^2 for the other two. These thresholds are about one order of magnitude larger than single DFB lasers in this material as can be seen from the Fig. 3(a). The unique selection of a single grating is

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therefore possible as long as the incident intensity is low enough. In this case, a change of the working wavelength is achieved by rotating the pump polarization angle, which allows for simple and rapid tuning of the output wavelength by means of a polarization controller, e.g., by using a liquid crystal polarization controller placed between the pumping laser and the multiplexed DFB film.

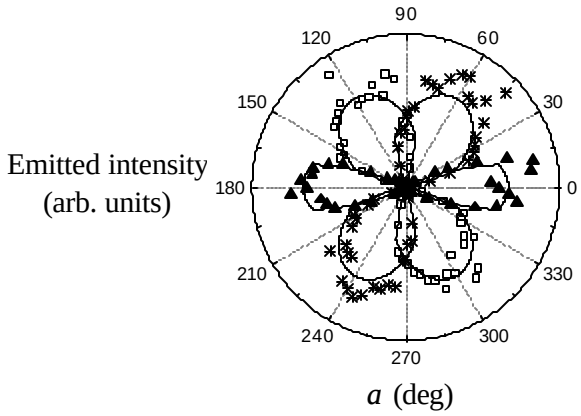

Fig. 5. The pump polarization dependence of the emitted laser intensity corresponding to the three multiplexed gratings. Open squares: peak at 630.6 nm, stars: 635.0 nm, filled triangles: 638.7 nm. Theoretical fits are described in text.

These devices have potential applications as compact, low cost, high-speed tunable laser sources. Another advantage of these systems is that the propagation direction of the different wavelengths is the same, allowing for compact devices. In fact, since the commutation time from one wavelength to another is only limited by the duration of the polarization change, the proposed structure is an attractive candidate for applications requiring high-speed tunability. The polarization selectivity of each grating can be controlled by adjusting the pumping intensity. In practice the number of superimposed gratings that can be individually addressed will be limited by the steepness of the transition from fluorescence to laser action, and the uniformity of grating preparation in a given sample.

4. Conclusion

In this work we have realized and characterized multiplexed DFB lasers in thin organic films of DCM doped PST-*co*-VBT. Single DFB lasers were shown to possess good laser characteristics and exhibit reasonable conversion efficiency, although this performance is diminished in the multiple grating structures. Films having three superimposed gratings were characterized in this paper, although structures having four gratings have also been fabricated and have the same properties. The pump polarization angle selectivity of the gratings allows for independent operation of each laser, and thus fast and simple tuning of the output wavelength. Furthermore, these structures open the possibility to encode the polarization of the pump beam in the output spectrum, making them attractive for polarimetry applications.[19]

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