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A two-dimensional liquid crystal (LC) laser array has been demonstrated by photopumping a single LC sample using a lenslet array consisting of plano–convex microlenses. A 5×5 array of LC lasers (displaying evidence of mutual coherence) spaced by 1 mm inactive regions has been generated, which could be combined to yield a single monomode output and allows an almost 50-fold increase in energy density in comparison to a single-focus LC cavity. Furthermore, we have demonstrated how the individual and recombined emission spectra vary with different sample topologies and how polydomain samples can be used to generate a multiwavelength laser emission. © 2008 Optical Society of America

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Band-edge lasing from liquid crystal (LC) media has been studied intensely in recent years because of its potential for applications requiring compact device architecture with wideband wavelength tunability [1–3]. In particular, reports have focused on functionality, emission characteristics, and the relationships between the performance metrics, such as the excitation threshold and slope efficiency and the macroscopic liquid crystalline properties [3]. The most common LC phase used in lasing experiments has been the chiral nematic (N^*) phase, which provides the photonic bandgap, while inclusion of a laser dye leads to low threshold lasing at the band edge. These samples are typically photoexcited using nanojoule to microjoule energy pulses (of nanosecond or picosecond duration) from a solid state laser (e.g., Nd:YAG). To achieve the energy density necessary to generate lasing from the LC sample, the pump source has to be focused at the sample to a small circular spot, typically of the order of 20–100 μm in diameter.

For the majority of the studies conducted on LC lasers hitherto, the sample is sandwiched between two glass substrates with total areas of the order of 1–5 cm^2. Consequently, this means that the majority of the LC laser sample is effectively redundant. In addition, pump beam intensities can sometimes be sufficiently high so as to induce local reorientation of the directors through thermal effects or photoinduced torques [4]. It can also lead to quenching and/or bleaching of the dye. In this Letter, we report on a two-dimensional LC laser array, which increases the spatial coverage of the active gain region within the sample. Furthermore, this approach seeks to increase the total output energy density, well above what would be achieved in a single cavity but without the undesirable effects caused by optically or thermally-induced reorientation and dye quenching. Finally, we report on how monodomain samples can be used to recombine the laser array into a single coherent source, while polydomain samples can be used as a potential source of simultaneous multiwavelength [white light or red–green–blue (RGB)] lasers.

To create the LC laser array, a lenslet array was used, which replaced the single plano–convex lens conventionally employed when photopumping an LC laser sample. The lenslet array (Suss MicroOptics) is made from fused silica (quartz), measuring 10 mm $\times$10 mm; it consists of a 10×10 array of square-shaped plano–convex microlenses, with a 1.015 mm pitch and a 28 mm radius of curvature, resulting in a focal length for each lenslet of ~60 mm (at 532 nm). The array is square-packed to maximize the fill factor (up to 98%) and also has an antireflection (AR) coating, optimized for the 400–900 nm wave band. When a collimated input beam is incident upon the array, the result is an array of focused spots, with 1 mm spacing, 60 mm away from the device, which could be used to optically excite the N^*LC cell. An illustration of the arrangement of the LC laser array is shown in Fig. 1.

The LC sample consisted of a mixture of E49 (Merck) doped with 4 wt % of a high twisting power chiral dopant, BDH1281 (Merck NB-C) and 1 wt % of the laser dye 4-(dicyanomethylene)-2-methyl-6-(4-dimethylaminostryl)-4*H*-pyran (DCM) (Lambda Physik). This mixture was capillary filled at room temperature into a cell consisting of two glass substrates, 10 μm apart, whose inner surfaces were coated with a polyimide alignment layer that had been rubbed in antiparallel directions. Two different cells were studied, filled with identical LC and dye but differing in the quality of their alignment. Cell A

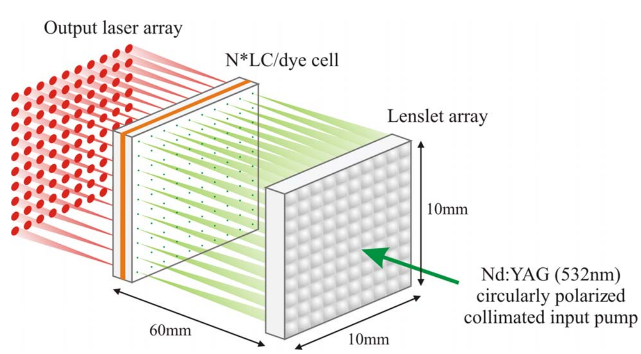

Fig. 1. (Color online) Illustration of the principle for photopumping an LC sample using a lenslet array that generates a diverging output laser array.

consisted of a high-quality LC alignment (uniform Grandjean texture) and could be approximated as a monodomain sample. Cell B had a lower quality of an LC alignment within it and was observed to be polydomain. The resulting dye-host mixtures were both measured to have an optical bandgap between 550 and ~650 nm and were designed with the intention of them lasing at the long-wavelength band edge. To generate lasing, the sample was optically excited by an Nd:YAG laser (NanoT, Litron), emitting 5 ns pulses at a wavelength of 532 nm (5.9 μJ per pulse) and a repetition rate of 4.2 Hz. To maximize the penetration depth of the pump beam, the emission from the Nd:YAG laser was converted using a Fresnel rhomb to a circular polarization of the opposite sense to that of the helix of the N*LC, thus avoiding the selective reflection that is associated with chiral photonic bandgap structures. Immediately after the sample, before the individual sources diverged and overlapped, a 4× microscope objective was used to collect the emission and therefore create a magnified image of the laser array. Long-pass filters were employed to remove transmission of the pump beam. All measurements were carried out at room temperature (23 °C).

Photographs of the illuminated lenslet array and the emission from the LC sample are shown in Fig. 2 (captured using a digital single-lens reflex camera, Canon EOS Rebel XT). Figure 2(a) is a magnified image of the illumination of the lenslet array by the pump beam. Figure 2(b) shows fluorescence within the active regions of the sample, each spot is separated by 1 mm from its nearest neighbor. From the photograph one can see that the spots at the center of the array have the brightest emission in accordance with the nonuniformity of the pump beam [cf. Fig. 2(a)]. In Fig. 2(c), a 4× microscope objective was placed a few millimeters from the LC cell, capturing and focusing the diverging laser emission as an enlarged array of spots, onto a white screen positioned 20 cm from the sample. In essence, a 5×5 laser array is shown, although some spots are missing from the top left and bottom right corners. In theory, more spots should still be visible; however, the nonuniform spatial variation of the pump beam intensity causes some of the active regions within the LC to be pumped at energy densities below their threshold for lasing. Finally, in Fig. 2(d), the microscope objective is removed. Individual diverging laser sources are therefore allowed to overlap and interfere with each other, generating the illustrated ring structure, which is similar to the Fraunhofer diffraction of a plane wave by an aperture. This interference pattern demonstrates a degree of mutual coherence between individual laser sources in the array and opens the possibility for the potential construction of high power organic thin-film lasers.

A typical intensity profile of the LC laser array for Cell A is shown in Fig. 3. To obtain this, the microscope objective was reinserted next to the LC cell, projecting focused individual laser spots onto a diffusing screen. A beam profiler (L230, Spiricon) combined with a telephoto lens then imaged the laser array emission. This beam profiler had a pixel pitch of 4.4 μm × 4.4 μm and a resolution of 1616 × 1216. It is evident from the plot that the distribution of the output energy is nonuniform and follows a similar pattern to the variation in pump beam intensity across the aperture as seen in Fig. 2(a).

The emission spectra of lenslet array pumped samples were found to be dependent upon the quality of the LC alignment within the cell. Figure 4(a) demonstrates the recombined spectral output for the monodomain Cell A. This was recorded by removing the microscope objective, which allowed the laser sources to diverge and overlap completely with one another before recombining them to a single spot with a condensing lens. The spectrometer was then positioned at the focal point of this lens and analyzed the total (recombined) emission from the sample. The spectra of individual laser sources in the array for

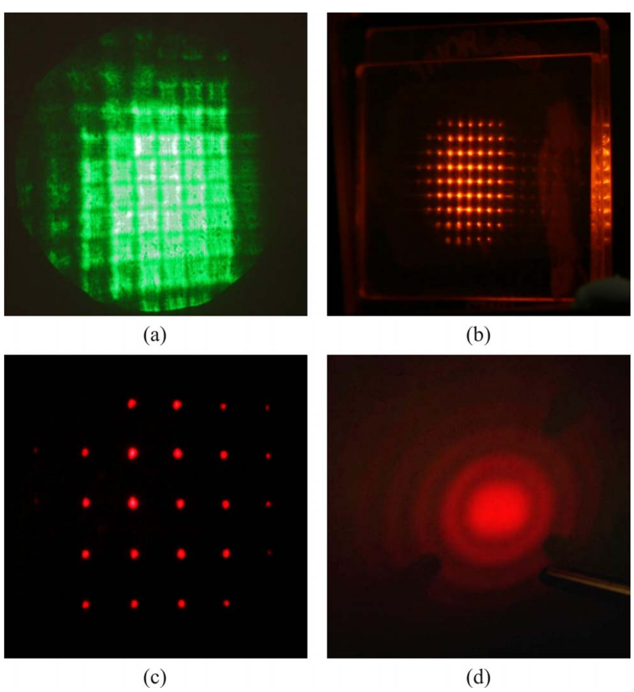

Fig. 2. (Color online) Photographs of (a) the lenslet array illuminated by the pump beam, (b) the active fluorescing regions within the LC, (c) the laser array emission, and (d) the interference fringes obtained when recombining the multiple laser emission sources (Cell A, monodomain sample).

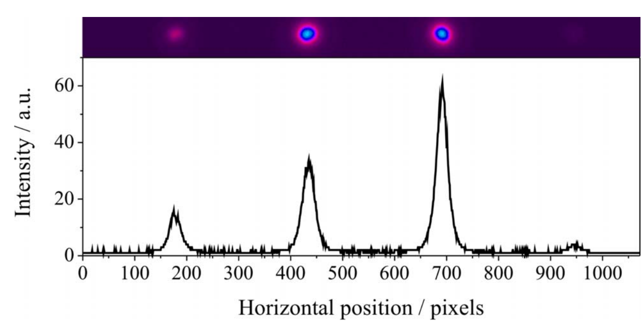

Fig. 3. (Color online) (top) Two-dimensional intensity profiles of the LC laser array emission for a typical row in the array, and (bottom) the corresponding cross section through the data (Cell A, monodomain sample).

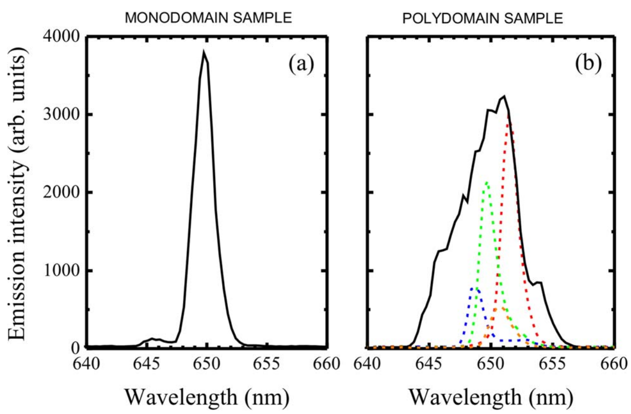

Fig. 4. (Color online) Emission spectra of two different LC laser array samples: (a) Cell A (monodomain sample), all individual laser sources are virtually identical, and the emission can be recombined to give an almost monomode output. (b) Cell B (polydomain sample), (broken curves) multiple monomode sources are achieved each arising from a different domain and chiral pitch (solid curve) and recombination of the laser array results in a broadband emission.

Cell A are virtually indistinguishable from the recombined data (except for an expected scaling in intensity). For each spot the full width at half-maximum (FWHM) of the emission spectrum was found to be of the order of 1.5 nm, which was at the resolution limit of our spectrometer.

Figure 4(b) shows, in the form of an envelope function, the recombined emission spectrum of all the sources in the array for Cell B (polydomain sample). It can be seen that the recombined emission spectrum is quite broad, extending from 644 to 656 nm. Within the recombined envelope, the spectra of four individual spots within the LC laser array are shown, each with a slightly different emission wavelength. Over the entire array the emitted wavelengths were found to vary over the range $\lambda = 648-654$ nm. This variation in lasing wavelength is due to subtle variations in the pitch of the N*LC across the cell. The laser wavelength is related to the pitch of the helix, p, and the refractive index parallel to the local director, $n_{\parallel}$, in the form $\lambda = n_{\parallel} p$ [5]. Consequently, over a distance of ~4 mm, the pitch was found to vary by the order of 3 nm. One should also note that the recombined emission from the polydomain sample (Cell B) is not symmetrical about the peak intensity as a result of the uneven distribution of energies over the laser array.

The average output energy per individual spot was measured to be 5.1 nJ per pulse, representing only 0.35% efficiency when totaled over the entire array. However, the efficiency of the system is currently not optimized. The laser emission wavelengths described in this Letter are at the long-wavelength side of the fluorescence curve of the DCM, ~40 nm away from the gain maximum (which has been shown to occur at 605–610 nm in LC solvents). Furthermore, it is intended to investigate shorter wavelength (and therefore more efficient) optical pumping with a more uniform spatial distribution of intensity. Additionally, by deliberately introducing divisions within the cell filled with different dyes and LC pitch lengths, it is hoped that simultaneous RGB laser emissions are possible from a single sample.

An important goal in LC laser technology is the realization of a continuous wave (cw) laser output with a low excitation energy density. To achieve this goal, using the conventional approach of a laser dye dispersed into an LC host, the problems associated with cw pumping must be circumvented. Previous studies have shown that at certain excitation energy densities the emission energy reaches a saturation limit before decreasing with increasing excitation energy. By combining the individual outputs from the laser array into one single output, higher outputs are possible than that which can be achieved when photopumping using a single-lens arrangement. Further rapid $x-y$ raster scanning of the individual monodomain LC laser cells may lead to a high repetition rate or quasi-cw output.

In summary, we have demonstrated lasing from an LC by photopumping using a lenslet array. This resulted in an LC laser array, in the present case, of 5×5 lasers and a single output when the lasers are recombined with suggestive evidence of mutual coherence between the individual outputs. Depending upon the topology of the sample, the recombined output is found to be either multimode or approaching single mode. For the latter to be observed, a large monodomain covering an area of 1 cm^2 was required.

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