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Implementation of a spatial light modulator for intracavity beam shaping

L Burger1,2, I Litvin1, S Ngcobo1,3 and A Forbes1,2,3

1 CSIR National Laser Centre, PO Box 395, Pretoria 0001, South Africa
2 Laser Research Institute, Physics Department, University of Stellenbosch, Stellenbosch 7602, South Africa
3 School of Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa

E-mail: lburger1@csir.co.za

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Abstract

In this paper we outline the steps necessary to create a laser with an intra-cavity spatial light modulator (SLM) for transverse mode control. We employ a commercial SLM as the back reflector in an otherwise conventional diode-pumped solid state laser. We show that the geometry of the liquid crystal (LC) arrangement strongly influences the operating regime of the laser, from nominally amplitude-only mode control for twisted nematic LCs to nominally phase-only mode control for parallel-aligned LCs. We demonstrate both operating regimes experimentally and discuss the potential advantages of and improvements to this new technology.

Keywords: laser beam shaping, resonator design, spatial light modulator

PACS numbers: 42.40.Eq, 42.40.My, 42.60.By, 42.60.Jf, 42.70.Df, 42.79.Kr

(Some figures may appear in colour only in the online journal)

1. Introduction

Good beam quality associated with lower-order modes is a fundamental requirement for industrial applications like cutting and welding that require a tightly focused beam. Applications such as paint stripping, penetration laser drilling and thin-film welding, however, require a flat-top beam profile, while high-volume parallel processes require a single beam to be split into an array of beams. The required beam shape for a particular application may be created by a range of techniques [1].

For example, a simple amplitude filter may be used to produce a Gaussian beam, but at the expense of power. A more efficient method of manipulating the intensity distribution of a given beam is using phase plates, but these are static, custom components, and their performance deteriorates with any variation in size of the initial beam [2]. Deformable mirrors were originally developed to correct for atmospheric disturbance in telescopes, but have proved useful for beam shaping applications, and have been used for producing circular and rectangular flat-top intensity profiles. They have the drawback however that the number of mirror elements is limited, and so the feature size of the beams produced by deformable mirrors is therefore limited [3, 4]. A more common approach today is to use liquid crystal (LC) displays in the form of spatial light modulators (SLMs) to dynamically mimic both amplitude and phase transformations. These devices are easily programmed by simply displaying the required phase, represented by a bitmap image, on the high-resolution SLM screen [5].

For the most part the aforementioned techniques are used to modify an existing beam outside a resonator, but it is possible to reduce the number of optical elements and increase the efficiency of a system by putting the modulating device inside the resonator. Intracavity amplitude filters, phase plates and deformable mirrors have all been used to modify the output beam [6, 7]. An intracavity optically addressed SLM has also been used to manipulate the beam intensity profile [8], but required a complex intracavity imaging system to create a phase screen. More recently we have demonstrated the on-demand creation of modes with an intracavity electrically addressed SLM [9–12]. The unique advantages of using an intracavity electrically-addressed SLM...
are the ability to create a very wide range of free-space beams, and the ability to do so dynamically.

In this paper we outline the necessary steps to construct a laser incorporating an intracavity electrically addressed SLM for transverse mode selection. We outline the design considerations, advantages and disadvantages of this approach, and provide a detailed performance evaluation of the SLM and laser. This work can be a useful reference for others wishing to build such devices.

2. SLM characterization and design considerations

In standard operation, each pixel on an SLM is addressed by a pixel on a grey-scale bitmap. For each pixel a grey scale level between 0 and 255 corresponds to a phase change of between 0° and 360° being imparted on the corresponding pixel on the SLM.

As will be seen in the discussion that follows, the most significant differences in performance of SLMs used as an intracavity component were a result of the type of LC used in the SLM. We consider here the two most common LC geometries: twisted-nematic liquid crystals (TN-LC), and parallel-aligned liquid crystals (PA-LC). Table 1 shows a comparison of typical specifications.

For most LCD applications a high resolution is regarded as being desirable. For SLMs used inside a resonator, however, the lower resolution of the PA-LC SLM presented no limitations.

Both types of SLM require linear vertically polarized light to perform optimally as phase screens, and behave as plane mirrors for light polarized perpendicular to this axis. It is therefore necessary to ensure vertical polarization in all experiments, and in the design of the SLM resonator. In addition, the possibility that either SLM would depolarize the beam was also considered. Experiments confirm however that there is no depolarization of the incident light on a single reflection off the SLMs for any phase.

Since the intracavity power is typically one order of magnitude higher than the extra-cavity power, one of the primary considerations is to prevent damage to the SLM. Depending on the expected intracavity power density it could be necessary to expand the beam in order to decrease the power density. Any clipping of the beam by the edges of the SLM active area will result in distortion of the desired mode. Using the second moment definition of beam radius, as a starting point the expected beam radius should be designed to be between 1/4 and 1/6 of the shorter dimension of the SLM active area. For example, the SLM with active area $15.36 \times 8.64 \text{ mm}$ would be illuminated by a spot radius no larger than 2.16 mm. An intracavity telescope is typically used to achieve this.

The zeroth-order reflectivity of the TN-LC SLM and PA-LC SLM were specified to be 60% and $>$90% respectively, with no specification given as to the variation in reflectivity with phase. The reflectivity of each SLM as a function of phase $R(\theta)$ was measured experimentally by reflecting a 1.064 $\mu$m Nd:YAG laser beam of constant power off the SLM and recording the reflected power. The grey level or phase shift of a uniform screen was increased in steps from 0 to 255 grey shades, or from 0° to 360°. The mean reflectivity of the TN-LC SLM over 360° was measured to be 51% for vertical (correct) polarization and 64% for horizontal (incorrect) polarization. The mean reflectivity of the PA-LC SLM over 360° was measured to be 91% for vertical (correct) polarization and 93% for horizontal (incorrect) polarization. One result of this is that a laser with this intracavity component will tend to produce radiation with polarization which is incorrect for the SLM, and that another polarization-selecting component needs to be included to ensure the correct polarization. Typically a Brewster window is used inside a cavity to select one polarization direction.

In conventional use, the beam reflected off an SLM is at a small angle from the incident beam, and a phase grating superimposed on the desired phase serves to separate the diffracted light away from the undiffracted light. Since it replaces a mirror, an SLM inside a resonator must be aligned perpendicular to the optical axis, with the reflected beam returning along the path of the incident beam, with the diffracted and undiffracted beams coaxial. Since a laser preferentially amplifies the mode with lowest loss, it tends to amplify the mode which is selected for by the SLM screen, and suppress any other modes, including that containing the undiffracted beam. In a similar way, as it is a pixelated device an SLM has the property of any periodic structure in that a small fraction of incident light is diffracted into higher orders. Fortunately these higher orders are diffracted away from the optical axis and lost, and only the lowest order containing the selected mode is amplified.

The average reflectivity of an SLM acts as a loss in the cavity, which can be compensated for with higher gain, typically by increasing the pump power. Far more important for our application is the variation in reflectivity with phase. The percentage variation in reflectivity was measured at 9.5% and 0.75% for the TN-LC SLM and PA-LC SLM respectively, as in figure 1.

The explanation for this variation in reflectivity can be found in [13], which explains that in TN-LC modulators with no field applied, the LC molecules are aligned in a 90° spiral between the front and back of the layer. When an electric field

<table>
<thead>
<tr>
<th>SLM type</th>
<th>Resolution (pixels)</th>
<th>Area (mm)</th>
<th>LC</th>
<th>Reflectivity</th>
<th>Damage threshold (W cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN-LC</td>
<td>1920 × 1080</td>
<td>15.36 × 8.64</td>
<td>TN</td>
<td>~ 60%</td>
<td>2</td>
</tr>
<tr>
<td>PA-LC</td>
<td>792 × 600</td>
<td>16 × 12</td>
<td>PA</td>
<td>&gt;90%</td>
<td>15</td>
</tr>
</tbody>
</table>
is applied across the layer, the LC molecules become tilted and cause an ellipticity in the polarization state. In TN-LC SLMs, the transmitted intensity is determined by the LC properties of twist angle and birefringence, as well as the orientation angles of internal polarizers which are used to cut out the nonlinear component. The result is an unavoidable amplitude modulation that can be reduced but not eliminated altogether [13–15], and therefore TN-LC SLMs are referred to in the literature as 'phase-only' or phase-mostly SLMs.

Remember however that SLMs are designed to be used as single reflectors, and in typical applications this residual amplitude modulation is negligible. Inside a laser resonator, however, it will be shown to have a determining effect on the laser performance. In PA-LC devices, the LC molecules are aligned in parallel, not in spirals, when no electric field is applied. When an electric field is applied the molecules are tilted in the direction of the substrates. When the polarization direction of the incident light is parallel to the axis of the LC molecules only the refractive index along the optic axis is changed, the light is not depolarized, and in theory phase-only modulation can be achieved [16–18]. In practice a small residual amplitude modulation can be measured, caused by reflection changes at the optical boundary and diffraction due to index changes of the LC material [19].

If \( R_i(\theta) \) is the reflectivity of the SLM, and \( R_2 \) is the reflectivity of the output coupler, then after \( n \) round trips through the laser cavity, a unit of intensity will have intensity \( I(\theta, n) \), given by

\[
I(\theta, n) = (R_i(\theta)R_2)^n.
\]

This simple amplification model reveals that this small variation in SLM amplitude modulation, when amplified through many round trips in a resonator, is sufficient to cause a higher lasing threshold at some phase values than at others. The model uses the amplitude modulation data from figure 1, and is used to generate the graphs in figure 2 which predict relative intensity as a function of phase after 0, 5, 10 and 20 round trips for the TN-LC SLM and the PA-LC SLM resonators respectively.

Figure 2(a) suggests that when a TN-LC SLM is used as an intracavity element, the variation in amplitude modulation which accompanies the desired phase modulation will be significant, and cautions that amplitude modulation effects could swamp the phase modulating effect. Figure 2(b) shows that any small residual amplitude modulation in a PA-LC SLM will have a far smaller effect on laser output, which will allow phase-only behaviour to dominate.

3. SLM laser description

Our experimental approach, illustrated schematically in figure 3, was to proceed in a step-by-step manner from a known, conventional resonator, through a series of equivalent resonators, ending with our goal configuration, and ascertaining equivalence in terms of the output beam at each stage.

The prototype SLM laser was constructed as shown in figure 4. It employed a 1% doped Nd:YAG crystal rod with
dimension of 30 mm (length) × 4 mm (diameter) as gain medium, which was end-pumped with a 75 W Jenoptik (JOLD 75 CPXF 2 P W) multimode fibre-coupled laser diode. A 4x Galilean beam-expanding telescope (BET) was used to increase the spot size on the SLM to 2 mm, in order to optimally fill the SLM while reducing the power density on it. The resonator was folded to facilitate the pump scheme, as well as to exclude the pump power from the leg containing the SLM.

Both the output coupler and the SLM were flat, and the resonator was marginally stable due to a small degree of thermal lensing. The output coupler reflectivity was 95%. In order to facilitate the alignment of the SLM, as well as to characterize the resonator without the SLM, the resonator included a flat 60% mirror immediately in front of the SLM on a flip-up mount (FUM). The nominal length of the cavity was 390 mm but was determined to have an effective length of 373 mm to compensate for the small thermal lensing due to pump absorption in the crystal as well as the refractive index of the crystal. The effective length was used in calculations of the beam sizes.

The laser included a BK7 Brewster window orientated at 56.4° to ensure that the beam was correctly polarized for the SLM. Filters separated the pump beam from the required beam, which was recorded using a Photon USBeamPro beam profiling system.

Two models, each with a different SLM, were constructed successively in order to evaluate the performance differences between the two systems. The TN-LC model included a 4x BET, but this was not included in the PA-LC model due to a higher SLM damage threshold.

4. Experimental results

The first prototype of a laser with an intracavity SLM included the TN-LC SLM. The initial equivalence of two configurations was tested: the resonator with a flat 60% reflectivity mirror (FUM up) as back reflector, and the same resonator with the TN-LC SLM with uniform phase as back reflector (FUM down). Both produced a Gaussian beam with radius 0.26 mm on the output mirror. Note however that the beam size on the SLM was many times bigger than this, and typically hundreds of pixels of the holograms will be used.

A lens phase pattern on the SLM, which is equivalent to a curved back reflector, resulted in the cessation of lasing instead of the expected change in beam size. Similarly, a linearly varying phase pattern also stopped lasing, instead of producing the expected misalignment effects. This indicated that when used in an intracavity configuration, the phase modulation effects of a TN-LC SLM are swamped by amplitude modulation effects and that it behaves primarily as an amplitude modulator. The bitmaps shown in figure 5 (bottom row) were generated in order to use this effect to select the laser mode in the manner analogous to the use of intracavity wires [20]. They consist of a geometric shape with a uniform grey level corresponding to the value for which minimum power output was obtained (grey level 85, phase
Figure 5. Beam patterns produced by the laser containing the intracavity TN-LC SLM are shown in the top row, with the corresponding bitmaps below each. The beams are identified as: (a) Gaussian beam; (b) Hermite–Gauss beam \((n = 1, m = 0)\); (c) eight-petal patterned beam, and (d) donut beam.

Figure 6. Examples of laser modes produced by the laser. In each case (a–h) the near-field pattern is shown, with the far-field pattern inset. Notice that the near-field beam pattern matches the far-field pattern. The modes can be identified as: (a) Gaussian; (b) Hermite–Gauss \((n = 0, m = 1)\); (c) Hermite–Gauss \((n = 1, m = 0)\); (d) donut mode; (e) Hermite–Gauss \((n = 0, m = 2)\); (f) Laguerre–Gauss \((p = 0, l = \pm 2)\); (g) Laguerre–Gauss \((p = 0, l = \pm 3)\); (h) Laguerre–Gauss \((p = 0, l = \pm 4)\).

Figure 7. Modal decomposition of the six-petal output pattern confirmed that it comprises a superposition of Laguerre–Gauss \((p = 0, l = \pm 3)\) and Laguerre–Gauss \((p = 0, l = -3)\) modes.

Figure 8. Changing the curvature \(C\) (where \(C = 1/R\)) on the digital holograms on the PA-LC SLM has the effect of changing the beam waist size on the output coupler.
superimposed on a uniform background with grey level corresponding to the maximum power output (grey level 225, phase $120^\circ$). The resulting laser beams are shown in figure 5 (top row), and confirm that the features behave as localized regions of loss: in figure 5(a) a uniform grey bitmap generates a Gaussian beam; in figure 5(b) a central horizontal strip forces the laser into a Hermite–Gauss beam ($m = 0$); in figure 5(c) a pattern of intersecting strips at $45^\circ$ to each other generates an eight-petal patterned beam; and in figure 5(d) a spot forces it into a donut-shaped beam.

The beam patterns were measured in the near- and far-fields for several output patterns (see figure 6). In each case the intensity distribution pattern in the near-field was the same as that of the far-field, which showed that these laser modes are also free-space modes and invariant on propagation.

Although the beams appeared to comprise of pure transverse modes, modal decomposition was performed on the six-petal output beam using the optical inner product technique [21]. This confirmed that it consists of Laguerre–Gauss modes ($p = 0, l = \pm 3$) with purity measured at greater than 90% (see figure 7). The reason for the high mode purity is that features on the SLM bitmaps serve as localized regions of loss along the nodal lines of a particular transverse mode, which results in a loss differential which selects for that mode and against all others.

In order to avoid thermal effects the SLM was mounted onto a heat sink, and the power incident on the SLM surface was limited to the manufacturer’s specified damage threshold. Priority was also given to minimizing thermal distortion of the laser crystal and other optical components, so most work was done just far enough above threshold to avoid flickering, with the output power not exceeding 200 mW. A weak thermal lens of about 25 m in the laser crystal caused the cavity to be stable even in a flat–flat configuration, and an unvarying mode was obtained from the system for periods in excess of an hour.

The second prototype used the PA-LC SLM as an intracavity component. To test whether the SLM screen serves as a phase modulator, an experiment was performed to determine whether a resonator containing an intracavity SLM displaying digital holograms of curved mirrors with radius of curvature $R$ does indeed produce beams equivalent to the identical conventional resonator, as required in figures 3(a) and (d). The beam waist $w_0$ on the output coupler was measured for a number of hologram curvatures as well as for two curved conventional mirrors and compared to the analytical expression [22]:

$$w_0^2 = \left(\frac{\lambda}{\pi}\right) \sqrt{L(R - L)},$$

where $L$ is the effective length of the resonator and $\lambda$ is the laser wavelength.

Figure 8 shows these beam size changes with hologram curvature.

The results in [9] confirmed that the amplitude modulation effects of an intracavity PA-LC SLM screen are negligible, and that it does indeed behave as a phase modulator.
The losses due to the SLM are higher than for physical mirrors (the threshold when the resonator contained the SLM was 27.5 W compared to 11.3 W with physical mirrors), but are easily overcome by increasing the pump power. The beams labelled (a)–(d) in figure 9 were produced using the corresponding digital holograms shown below each beam, and can be identified as (a) a circular flat-top beam; (b) an Airy beam; (c) a Laguerre–Gauss beam \((p = 1, l = \pm 2)\); and (d) a Laguerre–Gauss beam \((p = 1, l = 0)\).

The digital holograms required to produce beams (a), (b) and (d) in figure 9 contain only phase features, but the flexibility of the device was increased by incorporating a localized checker-board pattern to make use of a complex amplitude modulation technique [23]. This technique, used to produce beam (c) in figure 9 and shown in more detail below the beams, demonstrates that almost any required output beam can be achieved using digital holograms containing a combination of phase- and amplitude-modulation patterns.

5. Conclusion

While it is well understood how to use a phase-only (or phase-mostly) SLM in a conventional, single reflection configuration, the effects of subtle properties of an SLM become apparent when it is used as an intracavity component. For example, the average reflectivity over all phase is an unwanted loss in conventional use, but in intracavity use can be readily compensated for by increasing pump power and consequently has a negligible effect. Conversely, the variation in reflectivity is negligible in conventional use, but is amplified in intracavity use until amplitude modulation is obtained from an SLM which is nominally a phase modulator. In terms of mode selection, there is a significant advantage to placing an SLM inside a resonator, namely that laser resonators are very effective filters, with the ability to amplify only the mode with the lowest loss and to suppress any others. This results in pure output modes, free of any unwanted superimposed modes. A virtually infinite set of free-space output beams can be produced by this device by the judicious combination of phase- and amplitude-modulation techniques in digital holograms displayed on the SLM screen, limited only by the resolution of the SLM. In addition, changing a digital hologram on the SLM screen requires no realignment, and the output beam can be cycled at the SLM refresh rate.

The biggest limitation of this device is on the output power, which is imposed by the damage threshold of the SLM. Further experiments are planned to amplify shaped beams to higher power levels.

References

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