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Discontinuous phase elements for transverse mode selection in laser resonators

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Discontinuous phase elements can be inserted into laser resonators so that the lasers will operate with only one desired high order transverse mode. These elements introduce sharp discontinuous phase changes so as to result in minimal losses for a desired transverse mode but high losses to others. The basic principles, along with experimental results with Nd:yttrium–aluminum–garnet and CO₂ lasers, illustrating improved output powers with a high beam quality of low divergence, are presented. © 1999 American Institute of Physics. [S0003-6951(99)02610-8]

In a laser resonator operating with many transverse modes, each mode leads to a different divergence, so the emerging output beam quality is relatively poor. To improve the quality, it is best to reduce the number of the modes, preferably to a single mode. Typically, this is achieved by introducing an aperture inside the resonator, so as to lower the Fresnel number ($N_F = a^2/\lambda L$, where a is the aperture radius and L is the resonator length).¹ Optimally, the laser should operate with a single Gaussian shape TEM₀₀ mode. Unfortunately, the introduction of the aperture results in a significant reduction of the output power, since only a small volume of the gain medium is exploited.

In order to retain a high output power and yet improve the beam quality, several methods have been proposed to achieve a laser operating with a single, high order mode. These included the insertion of an absorbing wire grid or mask inside the laser resonator,² insertion of phase shifting masks,³ the use of conical resonator mirrors,⁴ and other specially designed mirrors.^{5–7} Unfortunately, these lead to either instabilities or losses or complicated resonator configuration or require external elements for ensuring that all portions of the output beam are in phase in order to improve the far field distribution.^{8–10}

In our research, we resorted to discontinuous phase elements (DPEs) that are inserted inside the laser resonators. These can be so designed to ensure that only one of the many transverse modes inside the laser resonator will be allowed to exist. The resulting output beam is thus stable, with low divergence and relatively high power. In the following we present the principles and design of these elements, along with representative experimental results for Nd:yttrium–aluminum–garnet (YAG) and CO₂ lasers.

The DPEs are more efficient for laser mode selection than the absorbing elements (such as wires or masks), because they rely on interference effects rather than absorption. For a phase step of π radians, such interference is exactly destructive, resulting in a higher loss than simple absorption. Furthermore, unlike the needed finite thickness (a certain

fraction of the mode width) for the absorbing wires, the DPEs can be infinitely thin with negligible absorption and consequently little losses for the desired mode operation.

In cylindrical coordinates, each mode is characterized by a radial node index p and an angular node index l . Specifically, the scalar field distribution $E(r, \theta)$ for a TEM _{p l} mode can be expressed by¹

$$E(r, \theta) = E_0 Q^{l/2} L_p^l(Q) \exp(-Q/2) \exp(-il\theta) \\ = R_p^l(r) \exp(-il\theta), \quad (1)$$

where r and θ are the cylindrical coordinates, E_0 the magnitude of the field, $Q = 2r^2/w^2$ with w as the spot size of the Gaussian beam, L_p^l are the generalized Laguerre polynomials of order p and index l , and $R_p^l(r)$ includes the r dependence of E . Due to symmetry, the modes of opposite angular momentum have the same radial distribution ($R^l = R^{-l}$), so they usually appear simultaneously, leading to

$$E(r, \theta) = R_p^l(r) \cos(l\theta). \quad (2)$$

Equation (2) indicates that with the exception of the fundamental mode TEM₀₀ all other modes will either have spots or rings or both, whose number depend on p and l . Also, adjacent spots and adjacent rings have opposite phases (π phase shift).

Now, in order to select a specific single high order mode operation, we insert into the laser resonator a DPE. As shown in Fig. 1, the DPE is inserted near one of the resonator mirrors, preferably near the output coupler mirror. The

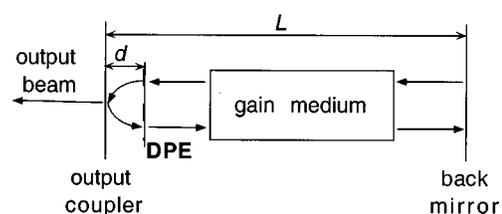


FIG. 1. Laser resonator configuration with a DPE inserted next to the output coupler.

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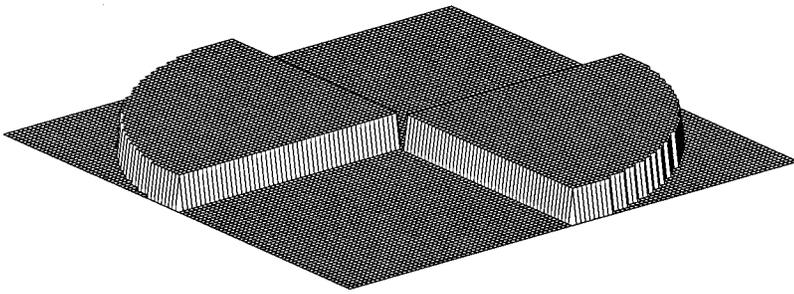


FIG. 2. The DPE shape for selecting mode TEM_{02} ($n=2$). The changes of the element parts correspond to phase changes of π .

DPE is designed to ensure that discontinuous phase changes of either 0 or π occur at the interfaces between adjacent parts of a desired mode distribution, where the intensity is very low.

Specifically, the DPE designed to select $l=n$, introduces an angular dependent phase shift, of the form

$$U(r, \theta) = \begin{cases} 0; & 3\pi/2 + 2\pi m > n\theta > \pi/2 + 2\pi m, \\ \pi; & 5\pi/2 + 2\pi m > n\theta > 3\pi/2 + 2\pi m. \end{cases} \quad m \text{ integer} \quad (3)$$

Note that for every (positive) value of n , a singular point appears in the origin of the DPE, which corresponds to the zero intensity in the origin for a TEM_{pl} mode with $l \neq 0$. A representative DPE, where $n=2$, is shown in Fig. 2.

As a result of passing through the DPE, adjacent spots and adjacent rings of the desired mode, which normally have opposite phases (π phase shift), will now have the same phase. The output mirror then reflects the modified mode distribution so it passes once more through the DPE, and all parts of the mode intensity distribution revert back to their original values. This is due to the fact that the total phase change introduced by the DPE is 0 or 2π .

If the distance d between the DPE and the mirror is sufficiently short compared to the resonator length L (i.e., $d \ll L$), then the overall distribution of the desired mode does not change as it passes twice through the DPE in a round trip. Specifically, the phase change introduced by the first passage is canceled by the return passage. However, all other modes, whose intensity distributions are different, suffer a sharp phase change at locations where their intensity is typically strong. Since $d \gg \lambda$, this leads to a strong divergence, where the phase change introduced by the first passage through the DPE is no longer canceled by the phase change introduced by the return passage. As a result, all modes besides the desired mode suffer a loss and most, if not all, are suppressed.

When the DPE is inserted next to the output coupler (as in Fig. 1), all parts of the desired mode distribution are in phase, so the far field of the output beam intensity has a high central peak, with some side lobes. Since the phase and amplitude of the output beam emerging directly from the laser are well defined, the output beam pattern may be further improved (e.g., to a TEM_{00} like shape, or other desired shape) by applying two external phase elements for obtaining amplitude and phase transformation.^{10,11}

Several DPEs, suitable for linearly polarized flashlamp pumped Nd:YAG and discharge pumped CO_2 lasers, were formed by means of photolithographic and etching pro-

cesses. For the Nd:YAG laser, the DPEs were formed on fused silica, and for the CO_2 laser they were formed on ZnSe substrates. All DPEs were antireflection (AR) coated. In both lasers, each having a length of 60 cm, the DPEs were inserted next to the output coupler.

Several theoretical and experimental representative results are presented in Figs. 3 and 4. Figure 3 shows results from the Nd:YAG laser in which was inserted a DPE designed to select TEM_{02} mode (such as shown in Fig. 2). Figure 3(a) shows the theoretical near field intensity distribution which was calculated by Eq. (2). The corresponding experimental near field intensity distribution, obtained with a charge coupled device (CCD) camera (Pulnix 765) is shown in Fig. 3(b). Both show the expected four lobes. Figure 3(c) shows the theoretical far field intensity distribution obtained

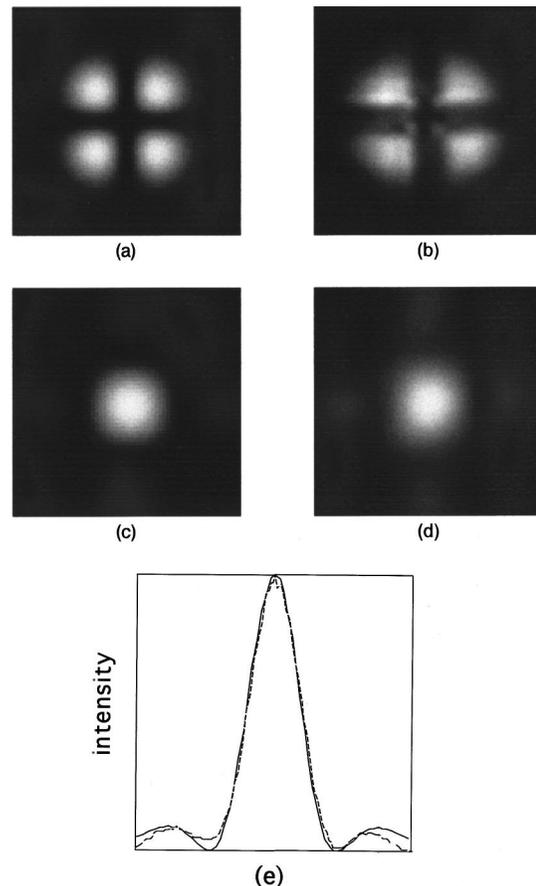


FIG. 3. Theoretical and experimental intensity distributions that emerge from a Nd:YAG laser in which a DPE was incorporated to obtain the TEM_{02} mode. (a) Theoretical near field, (b) experimental near field, (c) theoretical far field, (d) experimental far field and (e) theoretical (solid line) and experimental (dashed) cross sections along the center of the far fields, including the low side lobes.

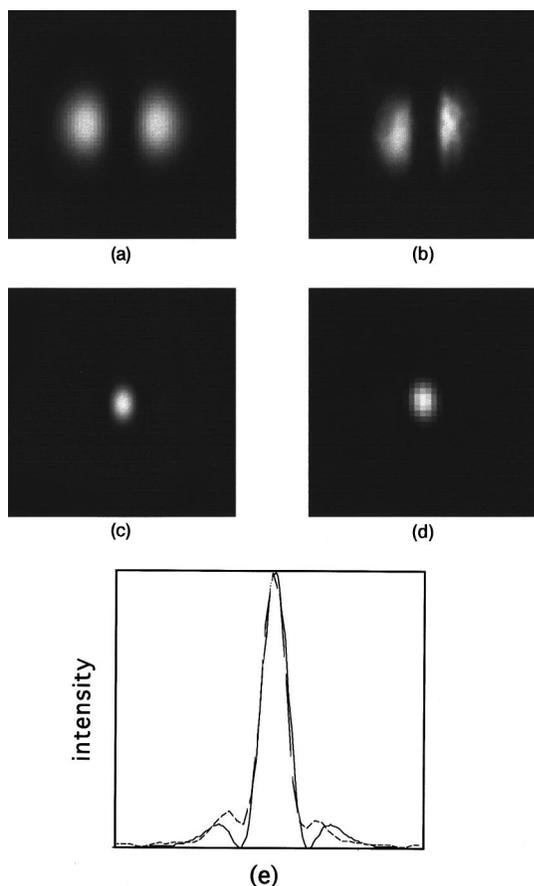


FIG. 4. Theoretical and experimental intensity distributions that emerge from a CO₂ laser in which a DPE was incorporated to obtain the TEM₀₁ mode. (a) Theoretical near field, (b) experimental near field, (c) theoretical far field (d) experimental far field and (e) theoretical (solid line) and experimental (dashed) cross sections along the center of the far fields, including the low side lobes.

after applying a Fourier transformation acting on the absolute value (i.e., all four lobes are in phase) of Eq. (2). Figure 3(d) shows the corresponding experimental far field intensity distribution. Figure 3(e) shows the corresponding central cross sections of the far field intensity distributions. As is evident, there is a strong central peak, indicating that all four lobes of the near field distribution are in phase. As expected, there are low intensity side lobes in the far field pattern in addition to the strong central peak. These side lobes account for the fact that we are exploiting a high order mode in the resonator.

With the DPE and an internal aperture set at $a = 1.1$ mm (i.e., $N_F = 1.9$) the output power was 3.5 W, this was higher than the output power of the single fundamental mode (TEM₀₀) which was obtained by reducing the initial aperture to $a = 0.7$ mm (i.e., $N_F = 0.77$). We chose an aperture of 1.1 mm, rather than no aperture, in order to suppress the existence of similar higher order modes, such as TEM₁₂.

Note however, that it would be possible to operate with no aperture, when a high order mode having a unique distribution is chosen. We repeated the measurements with an internal aperture set at $a = 1.1$ mm but without the DPE. This resulted in a multi-mode pattern in the near field, that could not be focused into a single main lobe in the far field, but resulted in a significantly wider intensity distribution.

Figure 4 shows results from the CO₂ laser in which was inserted a DPE designed to select the TEM₀₁ mode. Figure 4(a) shows the theoretical near field intensity distribution, which was calculated by Eq. (2). Figure 4(b) shows the corresponding experimental intensity distributions obtained with a pyroelectric camera. Both results show the expected two lobes. Figures 4(c) and 4(d) show the theoretical and experimental far field intensity distributions, with a high central peak and two low side lobes. Finally, Fig. 4(e) shows the corresponding central cross sections of the far field intensity distributions. Inserting an internal aperture set at $a = 4$ mm (i.e., $N_F = 2.5$), an output power of 3.7 W was obtained, with 80% of the power concentrated in the central lobe. This was higher by more than 50% than the output power of the single fundamental mode (TEM₀₀) which was obtained by reducing the aperture to $a = 3.4$ mm (i.e., $N_F = 1.8$). Finally, we compared the performance of our DPE with that of absorbing wires of various thicknesses.² The maximal single mode TEM₀₁ power of the CO₂ laser, obtained for a wire diameter of 75 μm, was 20% lower than with the DPE, confirming the advantage of our approach.

We presented a method in which discontinuous phase elements are inserted into laser resonators so as to obtain a stable operation at a single high order mode. As a result, more of the volume of the gain medium is exploited, thereby obtaining higher output powers. The method was illustrated with Nd:YAG and CO₂ lasers, but it is generic to many other lasers.

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