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Improving the stability of longitudinal and transverse laser modes

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Abstract

We show that laser mode stability can be improved with an intracavity mode selecting phase element. Without the phase element, a sub-wavelength change of the distance between the mirrors of a CO_2 laser leads to a substantial change of the transverse mode distribution, whereas with it the distribution remains essentially the same.

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In general, the modal content in a multimode laser depends on the laser resonator length. This leads to significant variations of the output intensity distribution from lasers where the separation between the frequencies of adjacent longitudinal modes is of the order of the laser gain bandwidth. In such lasers, e.g., CO_2 lasers, the effective gain of each transverse mode strongly depends on the exact position of its longitudinal mode frequencies with respect to the maximal gain frequency [1]. Hence, the transverse modal content becomes extremely sensitive to sub-wavelength changes of the laser resonator length. In principle, this strong coupling between longitudinal and transverse modes can be used for the selection of a single longitudinal and transverse mode by sub-wavelength adjustment the resonator length L, as we demonstrate below with an infra-red CO_2 lasers. Unfortunately, as the laser resonator length changes spontaneously on such sub-wavelength scale due to mechanical vibrations and thermal drifts, the selected transverse mode is extremely unstable.

In this paper, we demonstrate an approach for stabilizing the transverse mode structure in cases where there is strong coupling between the

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longitudinal and the transverse modes. In this approach, an intracavity phase element that discriminates and selects a specific transverse mode is inserted into the laser resonator. We show that the discrimination can be so strong that the selection of the single transverse mode remains stable despite changes of the resonator length. Such phase elements were used for increasing the output beam power [2–5] while maintaining good beam quality [6,7], in lasers with many longitudinal modes (e.g., >100 for YAG lasers [1,8]), where transverse mode stability is inherently insensitive to changes in the laser cavity length. Here, we investigate the influence of the phase elements on the laser mode stability, in the inherently unstable regime where the separation between the frequencies of adjacent longitudinal modes is of the order of the laser gain bandwidth.

To demonstrate our approach we used a representative continuous wave CO_2 laser. The laser resonator included a flat output coupler with reflectivity $R_1=95\%$ and a high reflective ($R_2=99.5\%$) concave back mirror with a curvature radius of 3 m. The resonator's length L was 165 cm, and the inner tube diameter was about 13 mm. No aperture was introduced, to allow for higher-order transverse mode operation. The back mirror was placed on a mount that allowed for sub-micron displacements along the axial z direction.

For the $He{:}N_2{:}CO_2$ laser gas mixture that was used, the average of pressure-broadening coefficients for different types of collisions is 5.87 MHz/Torr [8]. So, for a pressure of about 20 Torr, the total pressure-broadened homogeneous linewidth is approximately 120 MHz. The inhomogeneous Doppler broadening [8] at room temperature and 10.6 μm transition was calculated to be 70 MHz. Consequently, homogeneous broadening is dominant. The linewidth of the laser transition obtained from the convolution of the homogeneous and inhomogeneous linewidths is approximately 140 MHz, smaller than the spectral separation of the longitudinal modes, which for our laser is $c/(2L)=185$ MHz. This means that the laser can operate with a single longitudinal mode.

The resonance frequencies of longitudinal and corresponding transverse modes are [8]

$$v_{qnm}=\frac{c}{2L}\cdot\left[q+(n+m+1)\frac{\arccos(\pm\sqrt{g_1g_2})}{\pi}\right], \tag{1}$$

where q is an integer number which counts the longitudinal modes, n and m indices denote the order of nmth transverse mode, and g_1 and g_2 are the resonator g parameters [8] (for our laser, $g_1g_2=0.46$). The second term in the brackets originates from the Guoy phase shift of the nm-th transverse mode and gives the frequency-separation of the higher-order transverse modes $\Delta v_{\mathrm{trans}}$ for each given longitudinal mode q. For our laser configuration, this separation is $\Delta v_{\mathrm{trans}}=49$ MHz, and the higher-order transverse mode frequencies are clustered as satellite modes on the high-frequency side of each longitudinal mode, giving frequency-separation format somewhat between the near-planar and confocal configuration [8].

In order to discriminate and select the specific (0,1) Laguerre–Gaussian (LG) transverse mode, we used a binary phase element (BPE) [3]. To determine the effect of such a BPE, we calculate the ratio B of the small-signal gain to the gain threshold value [9] for the fundamental and (0,1) LG modes, given by

$$B=\frac{g_0L}{|\ln\sqrt{R_1R_2}V_{\mathrm{s}}|}, \tag{2}$$

where g_0L denotes the small-signal gain, $|\ln\sqrt{R_1R_2}V_{\mathrm{s}}|$ is the gain threshold value, and V_{s} is the single-pass diffraction loss factor. We assume other losses to be small. The V_{s} values were obtained by the round-trip matrix diagonalization method within a "strip" resonator model [10]. The small-signal gain was assumed to have the Lorentzian lineshape [8]. The calculated results are presented in Fig. 1. Fig. 1(a) shows the ratio B of the small-signal gain to the gain threshold obtained for the resonator without the BPE, while Fig. 1(b) – with the BPE. It is evident that without the phase element, Fig. 1(a), the curves obtained for the fundamental mode and (0,1) LG mode, cross each other. This indicates that by properly adjusting the resonator length L so as to control the longitudinal modes, it would be possible to obtain laser operation with different transverse modes. On the other hand, with the BPE, Fig.

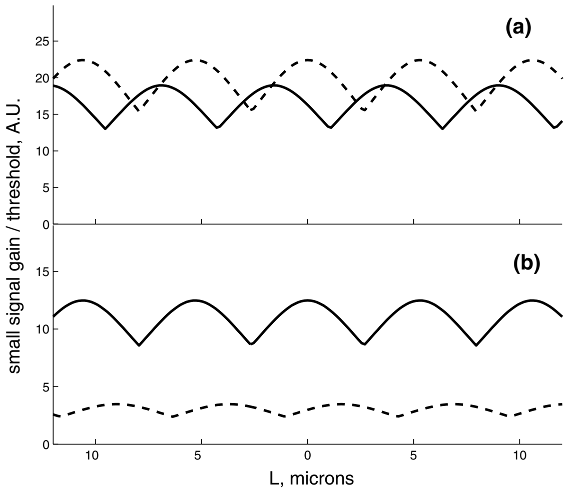

Fig. 1. Calculated ratio B of the small-signal gain g_0L to the gain threshold value $|\ln(\sqrt{R_1R_2}V_s)|$, for the fundamental (dashed curve) and (0,1) (solid curve) LG modes, as function of a slight change ΔL of the resonator length: (a) without BPE; (b) with BPE.

1(b), the curves obtained for the fundamental and (0,1) LG modes are separated, indicating that the laser will operate only in a single transverse higher-order mode.

Fig. 2 shows the experimental near-field and far-field intensity distributions, obtained with the laser that did not contain a BPE, for different resonator lengths. The upper row shows the near-field intensity distributions, while the lower row shows the far-field intensity distributions. From the left to the right, each subsequent distribution is detected after a slight change ΔL of the resonator length. The periodic change of the transverse modes is clearly evident, whereby each transverse mode is repeated, as expected, after $\Delta L = 5.3$ μm $= \lambda/2$. These results indicate that control of the longitudinal modes by adjusting the resonator length L allows selection of different transverse modes. Such a method for transverse mode selection is not very practical, because the resonator length is extremely sensitive to mechanical and thermal variations. Such variations can lead to change of the transverse modes with time. Moreover, the modes are not very pure. Indeed, it is evident from the Fig. 2 that the "Gaussian" distribution of the fundamental mode is too wide, because it is obtained with no appropriate aperture (we obtained $M^2 = 1.55$), and that of the (0,1)* LG mode is really a mixture of (0,1)* LG and Gaussian modes (we obtained $M^2 = 1.76$ for this "mode").

In order to improve the transverse mode stability, we incorporated a BPE designed to select (0,1) LG mode into the laser resonator at a distance of 3 cm from the back mirror. It was fabricated using

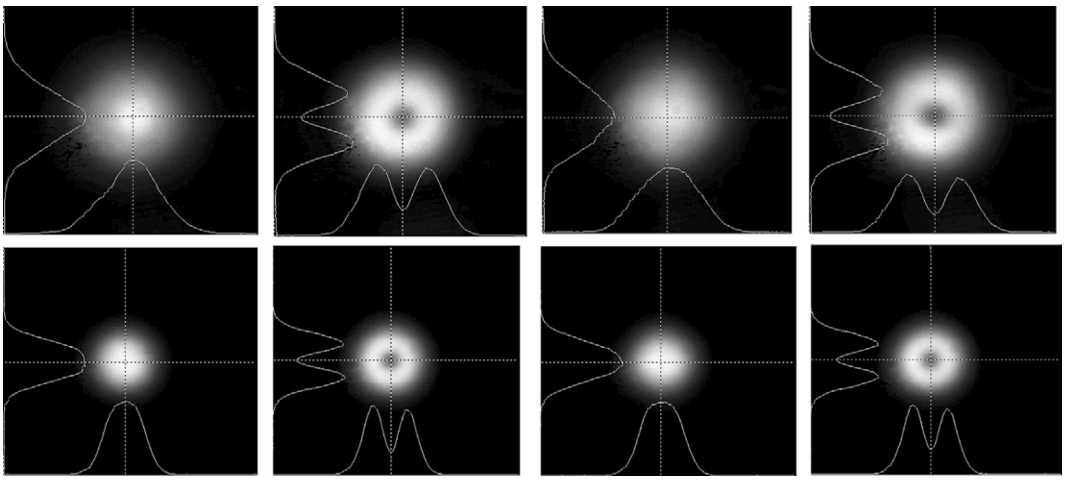

Fig. 2. Experimental near-field and far-field intensity distributions for different resonator lengths. From the left to the right, each subsequent distribution is recorded for the resonator length change $\Delta L = \lambda/6$, $\Delta L = \lambda/2$ and $\Delta L = 2\lambda/3$, whereby the period between two similar distributions is 5.3 μm $= \lambda/2$. Upper row: near-field intensity distributions; low row: corresponding far-field intensity distributions.

photolithographic reactive ion etching and antireflection coating technologies on zinc selenide substrates [4]. Configuration of the laser resonator containing the BPE, is shown in Fig. 3. The inset schematically shows the BPE profile. Fig. 4 shows the near-field and far-field intensity distributions, for different laser resonator lengths, with the BPE in the cavity. The upper row shows the near-field intensity distributions, while the lower row shows the far-field distributions. Each subsequent distribution, from left to right, is recorded after a slight change ΔL of the resonator length, whereby ΔL after two displacements is $\lambda/2$. As evident, the selected transverse mode does not change with the change of the resonator length L. This indicates that the mode will remain stable with respect to mechanical and thermal variations.

The variations of the intensity in the center of the output beam provide a good qualitative criterion for the transverse mode stability. We measured the intensity in the center of the output beam as a function of ΔL. The results are presented in Fig. 5. Curve (a) is for the laser without BPE, while the

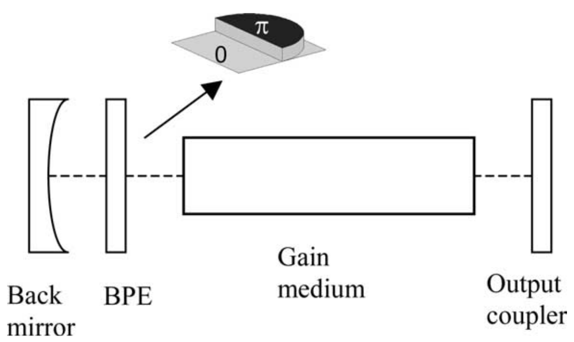

Fig. 3. Configuration of the CO_2 laser resonator containing the BPE. The inset schematically shows the BPE profile.

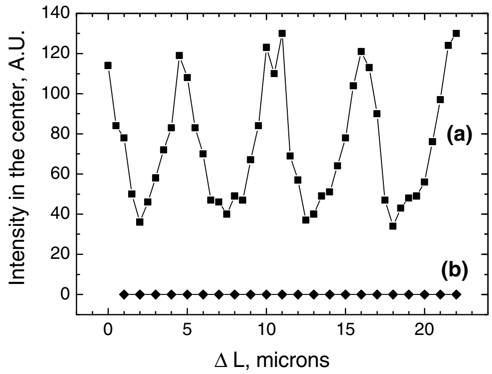

Fig. 5. Experimental near-field intensity in the center of the output beam, as a function of the change ΔL of the laser resonator length: (a) without a BPE; (b) with a BPE designed to select (0,1) LG mode. Note large periodic variations in curve (a) and total stability in curve (b).

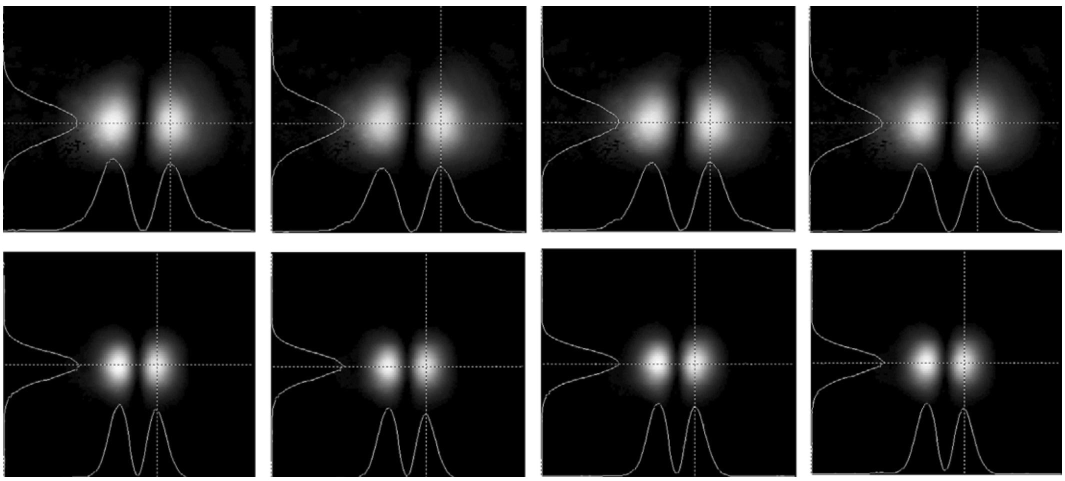

Fig. 4. Experimental near-field and far-field intensity distributions for different resonator lengths, with an intracavity phase element designed to select (0,1) LG mode. From the left to the right, each subsequent distribution is recorded for the resonator length change $\Delta L=\lambda/6$, $\Delta L=\lambda/2$ and $\Delta L=2\lambda/3$. Upper row: near-field intensity distributions; low row: far-field intensity distributions.

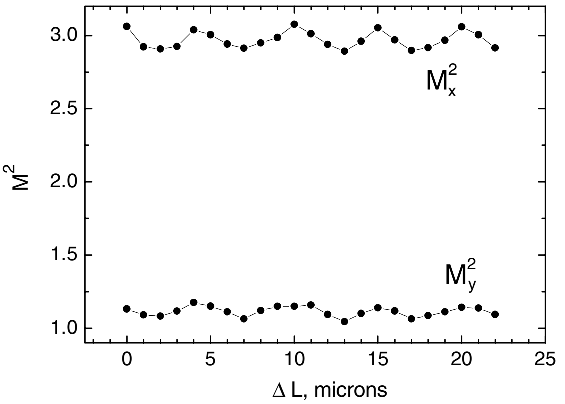

Fig. 6. Experimental M_x^2 and M_y^2 beam quality factors as a function of the change ΔL of the laser resonator length, with a BPE designed to select (0,1) LG mode. Note periodic 5% variation of M_x^2 and 9% variation of M_y^2, with the period of $\lambda/2 = 5.3$ μm.

curve (b) is for the laser with BPE designed to select (0,1) LG mode. As evident, without the BPE the intensity in the center shows strong periodic variations (with a period of $\lambda/2$), reflecting periodic change from nearly Gaussian mode distribution to a nearly (0,1)* LG mode distribution (see Fig. 1). On the other hand, the intensity in the center, obtained with the BPE, does not vary at all, demonstrating excellent stability.

To quantitatively characterize the stability of the (0,1) LG mode, selected with the BPE, we measured beam quality factor M^2 as a function of ΔL. The results are shown in Fig. 6. The upper curve denotes M_x^2 factor, while the lower curve denotes M_y^2 factor. The variation in M_y^2 factor is only 9%, while the variation in M_x^2 factor is only 5%. Also, we obtained periodic variation in the output power, which was of about 15%. These variations are due to the periodic variations of the resonance conditions as the resonator length L is varied.

In our experiment the laser efficiency, prior to inserting the BPE, was 10%, with the output power of 3 W. With the BPE, the output power decreased to 1.9 W, as expected from the effective mode area of the (0,1) LG mode as compared to the (0,1)* LG mode.

To conclude, we have shown that an intracavity phase element significantly improves transverse mode stability. Specifically, we experimentally demonstrated that the introduction of an intracavity phase element into a CO_2 laser essentially maintains the same single transverse mode, regardless of changes in the resonator length L. In contrast to this, without the phase element, the transverse mode is not maintained even with slight changes of the resonator length L.

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