Conversion of a high-order mode beam into a nearly Gaussian beam by use of a single interferometric element

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We present a new, compact, and practical optical mode converter that efficiently transforms a high-order Hermite–Gaussian (HG) laser beam into a nearly Gaussian beam. The mode converter is based on coherently adding different transverse parts of the high-order mode beam by use of a single planar interferometric element. The method, configuration, and experimental results obtained with a pulsed Nd:YAG HG TEM_{10} laser beam are presented. The results reveal that the efficiency of conversion of a HG beam to a nearly Gaussian beam can be as high as 90%. © 2003 Optical Society of America

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With efficient intracavity high-order transverse mode selection it is possible to increase the output power from a laser relative to that of a laser that is operating with only the fundamental TEM_{00} mode.[1–3] The increase in output power, which could be at least 50%, is accompanied by an increase in beam propagation factor M^2, which presumably degrades the inherent beam quality of the laser beam. Fortunately, because a pure high-order mode beam has well-defined amplitude and phase distributions, it is possible according to thermodynamic principles to transform the beam efficiently into a nearly Gaussian beam.[4,5] This fact clearly distinguishes a high-order mode beam from a multimode beam, whose poor beam quality cannot be improved without considerable loss. High-order mode conversion to a nearly Gaussian beam can be efficiently achieved, in principle, with two specially designed phase elements,[6] but their fabrication is usually impractical. Alternatively, a single spiral phase element has been exploited to transform a high-order $TEM_{0,1}{}^{*}$ beam efficiently into a nearly Gaussian beam, but such transformation is confined to a small class of helical mode beams.[7] Recently a new method for efficiently transforming a Hermite–Gaussian TEM_{10} mode (HG_{10} mode) laser beam into a nearly Gaussian beam was introduced.[8] This method is based on the approach of separating the beam into two parts that have well-defined relative phases and then recombining the parts coherently. The method requires careful alignment among several discrete mirrors, a beam splitter, and a phase-tuning plate for adjusting the relative phase.

In this Letter we present an alternative compact, stable, and practical transformation method in which a single planar interferometric element performs the needed separation and coherent recombination. Specifically, we show how to convert the HG_{10} mode beam into a nearly Gaussian beam by using a single element that performs both the separation of the two HG_{10} lobes and their coherent combination. The use of a single element is advantageous because it greatly reduces the complexity of alignment and significantly improves interferometric stability.

A basic configuration for generating a HG_{10} mode and converting it to a nearly Gaussian beam is presented schematically in Fig. 1. The laser resonator is designed to select the HG_{10} by using a suitable intracavity phase element, positioned near the rear mirror of the laser resonator, along with a suitable intracavity aperture for eliminating undesired higher-order modes. The phase element and aperture introduce low losses to the desired mode and high losses to all other modes, resulting in single-mode operation of the desired mode.[5] The external mode converter is a single element composed of a high-precision plane-parallel plate with specially designed coatings. Half of the front surface is coated with an antireflection (AR) coating, the other half with a 50% beam-splitter coating, and the rear surface with a highly reflecting coating. The plate is aligned at a 45° angle to the collimated input HG_{10} mode laser beam, so the dividing line between the beam-splitter coating and the AR coating exactly separates the two lobes symmetrically. One of the lobes is directly reflected

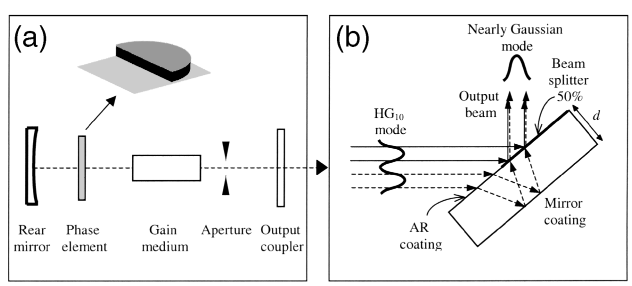

Fig. 1. (a) Configuration of the laser resonator designed for generating a HG_{10} mode beam. (b) Configuration of a compact and practical optical mode converter for efficiently transforming the high-order HG_{10} mode beam into a nearly Gaussian beam.

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from the beam-splitter coating region, whereas the other is transmitted through the AR-coated region, is reflected back from the rear surface, and exits the plate to be collinear with the other reflected lobe. The thickness d of the element is designed to produce the correct shift such that the two lobes optimally overlap and propagate collinearly at the output. For an incident angle of 45°, d is determined by the simple relation $d = x_0/\{\sqrt{2}\tan[\arcsin(1/n\sqrt{2})]\}$, where x_0 is the required shift between the two lobes and n is the refractive index of the material. The optimal shift was found to be $x_0 = 1.6w$, where w is the waist parameter of the HG_{10} mode beam.[8]

By fine tuning the angle of the mode-converter element, we can adjust the relative phase between the two lobes such that the fields of the two lobes add coherently. Because one of the asymmetric lobes is shifted toward the other, without rotation, the lobe distributions at the output cannot exactly overlap. Therefore there are some reflections of light back into the element and some consequent light power loss. It has been shown that for the configuration with several discrete elements and optimal coherent overlap, which includes the tails of the two HG_{10} lobes, the power loss is 1.5%.[8] With our compact mode converter, part of the tail of the transmitted lobe will not be reflected back into the mode-converting element, so power loss is reduced. Note that the addition of the light from the tail causes the quality of the output beam to deteriorate somewhat. The calculated power loss and M_x^2 as functions of the shift, for this case, are presented in Fig. 2. For example, we calculated a minimal power loss of 1.1% for a shift of $x_0 = 1.6w$, where the M_x^2 value was 1.54.

The operation of the compact mode converter was evaluated experimentally. For the experiment we used a pulsed (pulse width, ~120 μs), p-polarized Nd:YAG laser to obtain the HG_{10} mode beam. The laser configuration included a plano–concave 70-cm-long resonator ($R = 3$ m), an intracavity aperture of 1.9 mm, and a HG_{10} mode-selecting phase element positioned ~9 cm from the rear mirror. To conveniently obtain optimal overlap between the two lobes of the HG_{10} beam we externally magnified the beam, using a variable zoom telescope, to be compatible with the thickness of the mode-converting element. The mode-converting element consisted of a 3-mm-thick plate (parallelism, 1 arcsec) coated with the appropriate dielectric coatings for p polarization and aligned at an approximate angle of 45° to the input beam. The angle was fine tuned such that the fields from the two lobes added coherently at the output (note that fine adjustment of the angle had an insignificant effect on the relative transverse shift between the lobes). To eliminate ghost reflection from the AR-coated surface and other residual reflections we used a one-dimensional aperture with sharp edges that allowed only the combined output beam to pass.

The results are presented in Fig. 3. Figures 3(a) and 3(b) show the near- and the far-field intensity distributions, respectively, of the generated HG_{10} mode beam as detected with a CCD camera and a focusing lens of 1-m focal length. The calculated M^2 for this beam, which we obtained by measuring the second-order moments and using the explicit definition for M^2,[9] was 3.04 in the x direction and 1.16 in the y direction, indicating a nearly pure HG_{10} mode beam. Figures 3(c) and 3(d) show the respective near- and

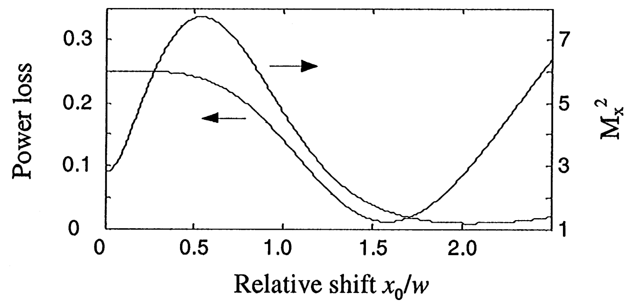

Fig. 2. Calculated power loss and M_x^2 as functions of the relative shift between the lobes when the two lobes of a HG_{10} beam are coherently added with the single interferometric element. It is assumed that part of the tail of the transmitted lobe emerges from the element through the AR-coated region.

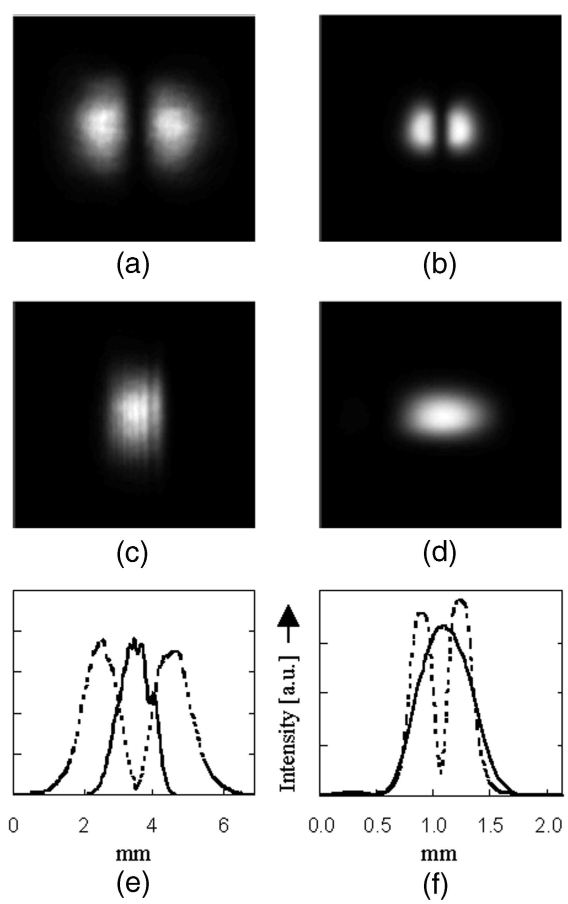

Fig. 3. Experimental intensity distributions of the HG_{10} mode beam and the combined output beam. (a), (b) Near- and far-field intensity distributions of the input HG_{10} beam; (c), (d) near- and far-field intensity distributions of the combined output beam; (e), (f) normalized near- and far-field intensity cross-section traces in the x direction, where the dashed curves represent the input beam and the solid curve represents the output beam.

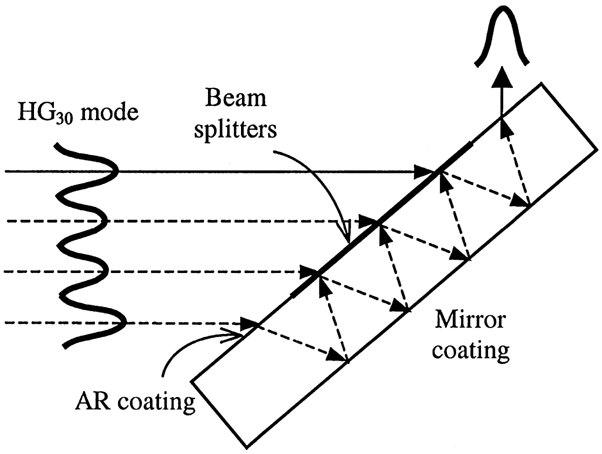

Fig. 4. Mode-converting element for transforming a HG_{30} beam into a nearly Gaussian beam.

far-field intensity distributions of the combined output beam that emerges from the compact mode converter. Figures 3(e) and 3(f) show the corresponding normalized intensity cross-section traces in the x direction; the dashed curves represent the input beam and the solid curves represent the output beam. As is evident, the recorded intensity distributions, in both the near and the far fields, consist of a single high-intensity lobe with nearly Gaussian profile cross sections in both axes. Using these results, we calculated values of $M_x^2 = 1.21$ and $M_y^2 = 1.05$ for the output beam, along with a 91% total measured power efficiency of the optical mode converter, i.e., 9% power loss. The results indicate that the ratio of the power to $M_x^2 M_y^2$ (proportional to the brightness) is increased by a factor of 2.5 after the beam passes through the mode converter and clearly demonstrates that the M^2 of the output beam is closer to that of TEM_{00}. The 9% power loss can be attributed to inexact overlap of the fields of the two lobes as well as to possible impurity of the original HG_{10} input beam, pulse-to-pulse fluctuations of its intensity distribution and direction, and imperfect dielectric coatings. Even with this loss, the results reveal a relatively efficient conversion to a nearly Gaussian beam.

The compact mode-converter configuration can be extended to transform higher-order Hermite–Gaussian mode beams into nearly Gaussian beams. In Fig. 4, for example, an element for transforming a HG_{30} beam into a nearly Gaussian beam is depicted. This element resembles the mode-converting element shown in Fig. 1, but its front surface is composed of multiple regions, each with a suitable coating. The first lobe of the HG_{30} mode (the bottom lobe) is transmitted into the element through an AR coating. Each of the successive lobes is transmitted into the element through a beam-splitter coating with a successively different reflectivity. Each beam-splitter coating is designed to achieve coherent addition between the field of the incident lobe and all the lower lobes, maximizing the confinement of light within the element. After all four lobes are coherently added, the combined output beam emerges from the mode-converting element through a region with AR coating. As before, the thickness of the element should be compatible with the distance between the lobes, and the angular orientation of the element should be fine tuned to adjust the relative phase between successive lobes. Such configurations could in principle be generalized to any HG_{NN} input beam by use of two suitable consecutive orthogonal mode-converter elements; however, with very high-order mode beams these configurations may not be practical because of power loss and design–fabrication complexity.

To summarize, we have presented a compact and practical optical mode converter that efficiently transforms a high-order HG_{10} mode beam into a nearly Gaussian beam. Because it utilizes only a single plane-parallel plate, interferometric stability is readily achieved. We verified its operation experimentally, obtaining a nearly Gaussian output beam with high efficiency. In principle, such converters could be extended to transform any high-order HG_{NN} mode beam.

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