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

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Received November 13, 2002

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

OCIS codes: 140.3300, 230.1150.

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. 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. 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, 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. 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. The 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. 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...
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 $45^\circ$, $d$ 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.

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 $1.5\%$.

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 $M^2$ 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 $M^2$ value was $1.54$.

The operation of the compact mode converter was evaluated experimentally. For the experiment we used a pulsed (pulse width, $\sim 120\ \mu s$), $p$-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 $45^\circ$ 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 $M^2$, 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 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. 2. Calculated power loss and $M^2$ as functions of the relative shift between the lobes when the two lobes of a HG$_{10}$ mode 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.](image)

![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.](image)
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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References