FIG. 7A shows a camera image of the far-field intensity of SLM-2 using the apparatus shown in FIG. 6.

FIG. 7B shows a camera image of the near-field intensity of SLM-2 using the apparatus shown in FIG. 6.

FIG. 7C shows a line-scan profile of the far-field intensity of SLM-2 using the apparatus shown in FIG. 6.

FIG. 7D shows a line-scan profile of the near-field intensity of SLM-2 using the apparatus shown in FIG. 6.

FIG. 8A shows a calculation of the field amplitude and the retrieved phase profile, corresponding to the experimentally measured intensity profile in the far-field of SLM-2, as shown in FIG. 7C.

FIG. 8B shows a calculation of the field amplitude and the retrieved phase profile, corresponding to the experimentally measured intensity profile in the near-field of SLM-2, as shown in FIG. 7D.

FIG. 9 depicts a single-pass MOPA system embodiment using a mode converter to transform a fundamental mode of a fiber laser (LP_{01}) into a specific high-order mode of a ribbon fiber amplifier, also, and a second mode converter to transform the HOM output of the ribbon fiber amplifier to a TEM_{00} mode.

FIG. 10 shows the single-pass MOPA system of FIG. 9, augmented with a real-time adaptive optical correction subsystem.

FIG. 11 shows a double-pass MOPA system with a mode converter, augmented with a phase-conjugate mirror to realize real-time adaptive optical compensation.

FIG. 12 shows a double-pass phase-conjugate MOPA system as in FIG. 11, augmented for phased-array power scaling using an ensemble of ribbon fiber amplifiers, cascaded in parallel.

DETAILED DESCRIPTION OF THE INVENTION

In this invention, we teach embodiments that can circumvent the prior-art system design tradeoffs described in the Background of the Invention. Embodiments are presented that enable one to utilize ribbon-core fiber amplifiers, enabling high-power scaling relative to that limited by circular-core fibers, which when combined with novel spatial optical mode transformers, can efficiently convert high-order ribbon-fiber modes to TEM_{00} fundamental modes, and vice versa.

The basic modal conversion, module involves a pair of diffractive-optic-elements (DOEs), situated at conjugate Fourier planes of an optical system. This configuration enables the transformation of a given input spatial profile to a specific output beam profile. As an example, a transformation module can be implemented to convert the diffraction-limited LP_{01} mode from a low-power fiber laser to a specific higher-order-mode (HOM) of a ribbon core fiber amplifier, and, subsequently, from the amplified HOM ribbon-fiber exit facet to a diffraction-limited TEM_{00} system output.

By extension, the final output beam can be in the form of an annular mode, which may be suitable for optically pumped laser gain media. Moreover, for specialized processing applications, the final system output can be in the form of a Bessel beam, with enhanced confocal parameters relative to a TEM_{00} beam. Our experiments show that the mode-conversion-efficiency exceeds 84% and, can theoretically approach 100%, while functioning at high-power and high-energy optical levels with little or no optical distortions.

In embodiments discussed herein, mode converters are utilized to interface active guided-wave devices into one or more other active guided-wave components, such as laser oscillators to laser amplifiers. In an embodiment of the present invention, the input to a mode converter is comprised of a master laser oscillator, whereas, the output is comprised of a single ribbon fiber amplifier or an array thereof. More specifically, in an exemplary embodiment, the input field to the mode converter system is a TEM_{00} beam from a low-power laser. The mode converter is designed to efficiently transform the TEM_{00} beam profile into a specific higher-order eigenmode of a ribbon fiber amplifier.

A further embodiment provides the means by which the now-amplified HOM output of the ribbon fiber amplifier is subsequently transformed to a desired TEM_{00} system output mode. This additional function employs a second mode converter, placed at the output facet of the fiber amplifier, with the converter comprised of a pair of DOEs similar to that of the first mode converter, but configured in a reciprocal arrangement. In both cases, the basic embodiments utilize a pair of non-identical phase plates, with each phase-plate placed at a respective conjugate Fourier plane of an optical system. In this invention, we teach designs for mode-converter systems that can theoretically approach 100% in absolute efficiency, insofar as converting TEM_{00} radiation, to the ribbon fiber's HOM, and, vice versa.

Exemplary embodiments that provide enhanced performance and power scaling are presented. In the former case, various classes of real-time compensation of optical distortions are described, with the potential to provide for diffraction-limited TEM_{00} output beams. In the latter case, the ability to scale the basic system to multiple ribbon fiber amplifiers, that function as a phased array, is presented. These systems have the potential to provide diffraction-limited, high efficiency operation at powers that far exceed the fundamental limitations inherent in single fiber amplifiers.

Basic Mode Conversion System

Turning now to FIG. 1, a drawing of a basic mode-conversion system is depicted. The system is comprised of a pair of diffractive optical elements, DOEs, 110 and 120, (DOE-1 and DOE-2, respectively), and a lens 130 of focal length, f. Each DOE is positioned at a respective focal plane of the lens 130, with the lens situated at the mid-plane between the pair of DOEs. The input optical beam to the system, $E_0=|g|e^{i\theta}$, is a complex electromagnetic field, characterized by an amplitude ($|g|$) 140 and a phase (θ) 145. The optical axis of the system is oriented along the z-direction, as shown. Upon propagation of the bean through phase-plate (DOE-1) 110, a spatial phase profile, $\xi(y)$, is imposed into the incident field E_0, resulting in a field $E_1=|g|e^{i(\theta+\xi)}$ at the front (upstream) focal plane of lens 130. (For convenience, we drop the explicit y-dependence notation of the amplitude and phase functions; it is to be understood that all such functions possess a transverse spatial dependence.)

In the case of an incident field whose beam waist is located at the plane of DOE-1, the initial input phase 145 is uniform. Hence, $\theta=0$, corresponding to the case of a fundamental spatial mode, with $E_1=|g|e^{i\xi}$. Upon propagation through the lens 130, the resultant EM field at the rear focal plane of lens 130 is given as $E_2=|G|e^{i\phi}$, with an amplitude ($|G|$) 150 and a phase (ϕ) 155. Assuming that the system satisfies the Fraunhofer approximation, it is well known that the complex EM fields at the respective focal planes of lens 130 are proportional to the spatial Fourier transforms of one another. That is $E_2 \propto \mathcal{F}\{E_1\}$, where $\mathcal{F}$ is the Fourier transform operator.

In the design of a passive mode converter the respective amplitudes, $|g|$ and $|G|$, of the respective input and output beams, 140 and 150, are either known or specified. It is a goal of this invention, therefore, to determine the necessary phase functions, ξ and ϕ, so that the mode converter will transform the given input amplitude 140 into the given, output ampli-