# DIFFRACTIVE OPTICAL ELEMENTS FOR TRANSFORMATION OF MODES IN LASERS

## CROSS-REFERENCE TO RELATED APPLICATIONS

This is a divisional of U.S. patent application Ser. No. 13/791,563 titled "Diffractive Optical Elements for Transformation of Modes in Lasers," filed Mar. 8, 2013, incorporated herein by reference. U.S. patent application Ser. No. 13/791,563 claims the benefit of U.S. Provisional Patent Application No. 61/641,464 titled "Diffractive Optical Elements for Transformation of Modes in Lasers," filed May 2, 2012, incorporated herein by reference.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the U.S. Department of Energy and Lawrence Livermore National Security, LLC, for the operation of Lawrence Livermore National Laboratory.

## BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to fiber amplifiers, and more specifically, it relates to techniques for increasing the high average power produced by fiber amplifiers.

2. Description of Related Art

Scalable, high average power lasers are needed for materials processing and defense systems. Scientific applications such as laser-based guide stars for astronomy, gravitational wave detection, coherent remote wind sensing and laser-based particle acceleration could also benefit from high-average-power lasers with diffraction-limited output radiation in a $TEM_{00}$ (lowest-order) spatial mode. Considerable attention has been focused on fiber-based lasers and amplifiers due to their potential for high average power combined with high beam quality and efficiency, compactness, and reliability.

Ytterbium doped fiber lasers and amplifiers at 1 μm have recently made tremendous progress and have been scaled to the multi-kW average power level with diffraction-limited beam quality. These systems are based on large-mode-area (LMA) step-index and photonic crystal (PC) based fiber amplifiers. The typical approach to power scaling in these fiber amplifiers is to increase the core size in each successive amplifier stage (while reducing the numerical aperture to maintain single-mode radiation), since nonlinearities and facet-damage power thresholds increase with increasing mode-field-diameter (MFD).

In typical high-power laser systems, a multi-stage optical configuration is employed, whereby a low-power, stable laser oscillator feeds one or more laser amplifier stages. Such configurations are known in the art as master oscillator power amplifier (MOPA) systems. The master oscillator, or, seed laser, typically provides high-quality diffraction-limited radiation in a fundamental $LP_{01}$ (or, $TEM_{00}$, etc.) spatial mode, which is comprised of a single-lobed output profile.

Given that a HOM, in general, is comprised of a complex, multi-lobed optical profile, a spatial mode converter is required to efficiently couple a $TEM_{00}$ mode from a seed oscillator into a desired HOM (or, superposition of HOMs) of a ribbon fiber amplifier. Similarly, since many laser applications require diffraction-limited $TEM_{00}$ output radiation, the ribbon fiber's output HOM radiation needs to be converted back to a $TEM_{00}$ mode, to complete the MOPA chain. To be of practical use, such a mode converter must be efficient (in terms of the ability to convert a $TEM_{00}$ mode into a desired HOM), low loss, and furthermore, capable of handling high optical powers, with minimal distortion and/or depolarization.



Mode conversion has recently been accomplished for circularly symmetric laser outputs via interferometric elements and mode coupling in dual-core PC fibers. However, these prior-art approaches tend to be quite complex and/or inefficient, especially, as the mode number is increased. Another conversion approach based on diffractive optical elements (DOEs) has been implemented for a number of years, for example, to transform annularly shaped output beams, typical of high-power $CO_2$ lasers, to a uniform spatial amplitude profile output, with a well-defined phase profile.

Siegman, early on, showed that for any near-field electric field profile, with a purely real-valued wave front, but with regions of positive and negative phasefront sign, a single DOE, in the form of a binary phase plate, does not improve the resultant beam quality, as measured by the well-known $M^2$ criterion. Specifically, this class of DOE mode converter results in far-field optical profiles that possess significant (undesirable) energy in its side-lobes, leading to no change in the $M^2$ figure-of-merit. Subsequently, it has been shown that mode converters comprised of either a single DOE (phase plate) or a continuous phase plate, when combined with a spatial filter can, in fact, improve the qualitative beam quality, in terms of the shape of its spatial profile, of a laser operating in a single higher-order-mode. However, in these approaches, the absolute conversion efficiency suffers, since energy in the side-lobes of the resultant beam is rejected by the spatial filter(s).

In the prior art, mode converters have been investigated to transform active optical sources into a single, composite beam. In one example of the prior art, the system was comprised of a phased array of VCSEL oscillators, whereas, in another example of the prior art the system was comprised of a sparse array of laser oscillators. In both cases, a mode converter was used to provide a $TEM_{00}$ output beam. Hence, the prior art systems demonstrated the capability to realize a free-space optical beam from an active array of devices.

A rectangular-core or elliptical-core fiber that guides and amplifies a higher-order guided mode can potentially be scaled to much higher-average-power amplification than what is possible in traditional circular-core, large-mode-area fiber amplifiers. Many applications require diffraction-limited $TEM_{00}$ output beams to be of practical use, owing to the single-lobed output profile characteristic of these guided modes. Since fiber amplifiers with higher-order mode output profiles possess multi-lobed transverse spatial profiles, systems with higher-order mode amplifiers are of limited use for many real-world scenarios, in spite of the fact that they enable scaling to much higher powers than are possible with conventional $TEM_{00}$ based fiber amplifiers. Hence, in the prior art, there is a system tradeoff regarding operation using a single-lobed, fundamental spatial mode versus power scaling considerations, typical of circularly symmetric large-core fibers.

## SUMMARY OF THE INVENTION

We have theoretically analyzed the limits to power scaling of these fiber amplifiers by considering thermal, non-linear, damage and pump-coupling limits as well as fiber's MFD limitations. Our analysis shows that if the fiber's MFD could be increased arbitrarily, 36 kW of power could be obtained with diffraction-limited quality from a fiber laser or amplifier.