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Continuous-wave all-fiber MOPA with SBS phase conjugate mirror

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ABSTRACT

A CW Nd:YAG master oscillator – fibre power amplifier (MOPFA) with fiber based SBS phase conjugate mirror is reported. A two-pass amplifier configuration is employed to compensate beam distortions in the multi-mode diode pumped Yb-doped fiber amplifier in conjunction with a fibre phase conjugator. The compensation of distortions is observed with ~30% of the total reflected power being of diffraction limited quality. Possibilities for improving the beam quality and power scaling in this system is proposed.

Keywords: Fibre amplifier, stimulated Brillouin scattering, phase conjugation

1. INTRODUCTION

Cladding-pumped fiber technology has revolutionized fiber lasers increasing their output power to well above 100 W in single transverse mode [1]. Alluring advantages over traditional solid state laser systems including higher efficiency, beam quality and compactness have opened up the prospects for wide ranging applications. Of these the most promising are expected to be in industry and defense systems as soon as the output power of such lasers may be scaled to the multi-kW level. Currently such output power is available from multi-mode fiber laser systems only [1], [2], [3]. Optical damage in the fiber core is the main limiting factor for power scaling of single-mode fiber lasers. Some progress has been made through the use of single-mode fiber with low numerical aperture (NA) and so large-area core [4], but the achieved power was far below the kilowatt level. Another option discussed in the literature for power scaling of single-mode fiber laser systems is the injection locking[1] of an array of fiber amplifiers [5], though the issue of coherent beam combining of the output radiation from such arrays has so far not been resolved. The use of phase conjugation (PC) for achieving diffraction-limited output from large core diameter fiber amplifiers was proposed and treated theoretically in [6] and scaling of a system consisting of a single-mode low power master oscillator - multi-mode fiber power amplifier with a fiber based SBS PC mirror to greater than 1 kW output power was predicted.

In this work we investigate the use of a CW master-oscillator fibre power-amplifier (MOFPA) scheme in which phase conjugation through SBS in an optical fibre is utilised for achieving diffraction-limited polarised output from a multimode amplifier.

2. EXPERIMENTAL SETUP

The optical arrangement of the MOFPA system, comprising a two-pass amplifier configuration and a fiber phase conjugate SBS mirror is schematically shown in Fig.1. The CW ring-cavity master oscillator (CW Nd:YAG Laser) was operated in a single transverse and longitudinal mode (spectral bandwidth of ~40 kHz [7]) with output power variable between 0 and ~2 W at 1064 nm. The laser head was the commercial unit (Spectron Laser Systems SL 903) comprising a Nd:YAG rod of 4 mm diameter and 103 mm length doped to a concentration of ~1% Neodimium and pumped by CW Krypton arc lamp F900-4. The linear polarized oscillator output beam was directed through a Faraday isolator (FI) to an amplifier (FA). A half-wave plate (λ/2) was used for turning the polarization vector of the radiation by 45° to restore it in the vertical direction.

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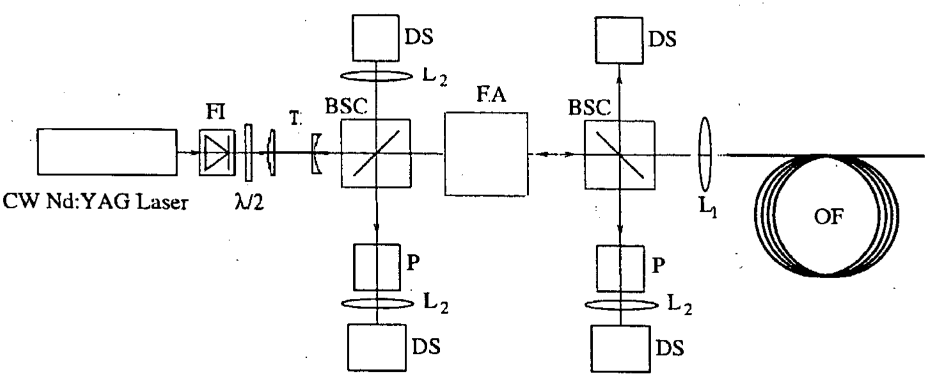

Figure 1. Experimental layout.

A telescope (T), formed by positive and negative lenses, was used to minimize the regular spherical component of the incident beam divergence and for matching the beam diameter to the aperture of the amplifier (FA). After the telescope the beam was of ~2 mm FWHM diameter with diffraction limited divergence of ~0.5 mrad. The radiation passed through the amplifier was sent to the phase conjugate mirror (PCM) consisting of a 5× microscope objective (L_1) and a standard graded index silica multimode optical fiber (OF) of 50/125 μm core/cladding diameter and of 3.6 km length ("Optical Fibres" Co., UK). Non-polarizing beam splitters (BSC; ~10/90) were placed between the telescope and the amplifier, and between the amplifier and PCM for recording the energy, spatial, temporal, spectral and polarization characteristics of the radiation by detection systems (DS). We used Coherent 210 and Coherent "FieldMaster" power meters, a CCD camera (COHU 4710) incorporated with an optical 2× wedge [8] to simultaneously monitor the far- and near-field patterns at different signal strengths, fast photodetectors BPX-65 connected to a LeCroy 9354L digital oscilloscope, and polarising beamsplitter cube (P) for such measurements [7].

Figure 2 shows the scheme of the fiber amplifier (FA in Figure 1).

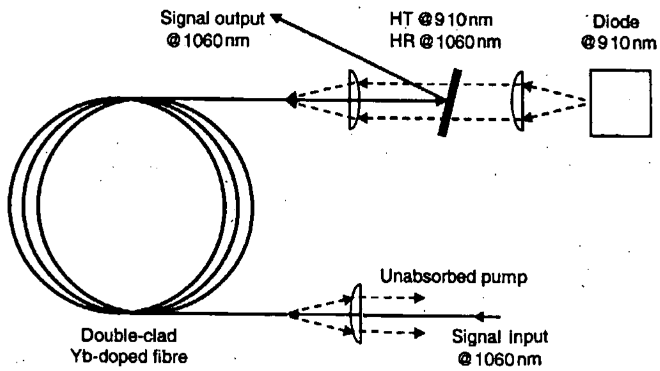

Figure 2. Diode pumped Yb-doped fiber amplifier arrangement. HR: high reflectivity, HT: high transmission.

A 6.4 m long fibre with a 30 μm diameter, 0.1 NA Yb-doped core was used. The ends of the fiber were angle-cleaved (~80°) to prevent self-oscillation. A 910 nm fiber-coupled diode laser with 3.5 W power at the output of a 0.22 NA pump beam delivery fiber was used as a pump source. The pump radiation was coupled to the cladding of the fiber amplifier through a combination of lenses and, and a dichroic mirror. The pump launch efficiency was ~ 70% with ~ 55% of the launched radiation absorbed in the fiber.

3. RESULTS OF MEASUREMENTS

The amplifier output power versus input power is shown in Figure 3.

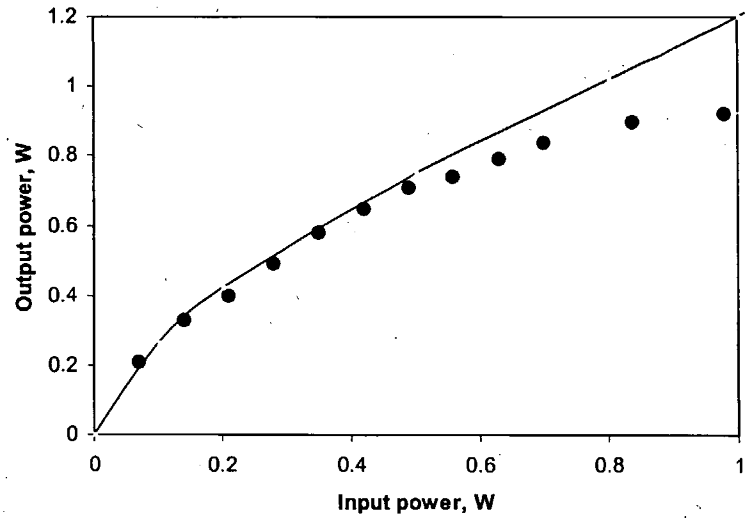

Figure 3. Measured (dots) and calculated (line) output versus input power of the fiber amplifier.

The obtained dependence is in reasonable agreement with the well known expression [9]

$$\ln[P(L)/P(0)] = g_0 L - \{[P(L)/P(0)] - 1\}[P(0)/P_S] \quad (1)$$

where g_0 and L are the unsaturated gain coefficient and length of an amplifier, P(0) and P(L) are input and output powers, P_S is the saturation power. The results of calculations for $g_0L = 4.9$ and $P_S = 0.045$ W are in reasonable agreement with experimental measurements. The low value of amplifier saturation power in this case is determined by the available pump power. The essential difference between the measured and the calculated dependencies at high input power is probably due to the residual losses in the amplifier which are not taken into account in Eq.(1). It follows from Figure 3 that the amplifier provides a net single-pass gain of ~3 for a small input signal, decreasing to ~1 for 0.9 W input signal power.

The amplified signal beam was spatially degraded and partially depolarised. Figure 4 shows far field power distributions of the input (4a) and output (4b) beams.

In the near field the spatial distribution of the amplified radiation consisted of a central peak, being the radiation from the master oscillator passed through the active core, and wings, arising from the radiation passed through the cladding. Measurements showed that ~25% of the input beam power propagated through the cladding. Since the divergence of this radiation is much higher than that for the radiation passed through the active core, it is not observable in the far field pattern (Fig.4b). The polarisation for the amplified radiation was found to be of elliptical form with a ratio of axes 1:3.

This radiation was sent to the SBS-PCM. The SBS signal was observed first when the output power from the amplifier was ~0.4 W. Taking into account the spatial distribution of the incident radiation and coupling losses the SBS threshold and SBS reflectivity was estimated to be ~0.26 W and ~20% for a PCM input power of 1 W respectively. These values are in reasonable agreement with our earlier measurements in this fiber [10] when depolarisation is taken into account [11].

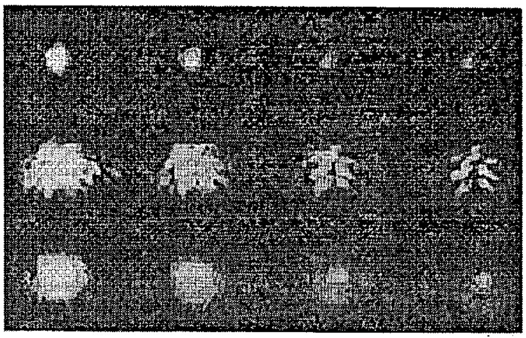

Figure 4. Far field distributions of radiation (a) from the master oscillator, (b) after single-pass amplification in the fiber amplifier and (c) after two passes through the fiber amplifier with reflection by the PCM.

As seen in Fig.4c, after the second pass through the amplifier the beam quality of the signal is improved, though it was not quite diffraction limited. Actually only ~30% of the total output power was restored to the divergence of the incident beam. There are two primary reasons for this incomplete restoration of beam quality: i) excessive coupling losses of radiation in the system because of non-optimised geometrical and numerical apertures of the fibers and lenses used in the experiment, and ii) depolarisation of radiation in the amplifier; both cause loss of information about distortions in an amplifier, and consequently decrease the efficiency of beam clean-up by phase conjugation [11], [12].

Furthermore the high level of losses along with low saturation power in the amplifier also resulted in low net energy efficiency in the system under test. The measured output power after two-pass amplification with reflection by the PCM was ~70% of the input power from the master oscillator, which is in consistence with measured values of the amplifier gain and saturation power, PCM reflectivity and estimated level of losses.

From analysis of these results it follows that in developing this technology to a practically useful MOFPA with a fibre SBS PCM will require a reduction of aperture losses in the system, suppression of radiation depolarisation in the amplifying fiber and an increase of pump power to the amplifier. To this end punda-type fibre with increased core diameter will help to decrease the depolarisation and aperture losses. The high damage threshold of such fibres will also benefit the goal of power scaling of this system to the kilowatt level.

4. CONCLUSIONS

We have designed and investigated a first test of principle CW MOFPA with fibre based SBS-PCM. The effect of beam clean-up by phase conjugation has been realised in this system. We have shown that for achieving high fidelity beam clean up through our phase conjugation technology it is necessary to: i) suppress the depolarisation of the radiation in the fiber amplifier, and ii) reduce the aperture losses in the system. We foresee that with these improvements the potential of the system for delivering diffraction limited output power scalable to the kilowatt level predicted in [6] may be realised.

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