Multi-kilowatt Peak Power Transmission through Infrared Fibers in the 3 - 5 μm Region

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ABSTRACT

We have demonstrated high power transmission through selected chalcogenide glass clad fibers using an Optical Parametric Oscillator (OPO) with output in the 3 - 5 μm wavelength region. These results show great promise for implementing these fibers to connect the laser to the Jam Head in IR Countermeasures systems. The maximum peak power used was 26.9 kW and the peak power density at the focus into the fiber was 1.07 GW/cm^2, which to our knowledge is the highest reported for these types of fibers. Results will also be shown of analyses of the near field profile exiting the fibers, in which no speckle was observed in the output distribution due to the large spectral bandwidth of the OPO. Such a smooth spatial profile is desirable for systems where the output needs to be free from "hot spots" or distortions which are usually obtained with multimode fiber laser delivery.

1.0 INTRODUCTION

NRL is currently developing chalcogenide glass fiber cables for connection of the laser to the Jam Head in IR Countermeasures systems, including the system under development for the Multispectral Countermeasures ATD (supported by U.S. Army CECOM, Ft. Monmouth, NJ). When compared to an open beam path (such as a mirror-based mechanical arm), a cable link has distinct advantages, such as simple and robust alignment from the laser to the Jam Head, flexibility of placement of laser and Jam Head in the aircraft, resistance to platform vibration and flexure and crush resistance. Chalcogenide glass fibers are not available commercially with low optical loss in the critical 2-5 μm wavelength region. Low optical losses in fibers of sulfide-based glass compositions (which are most suitable for this region) have been achieved due to advanced purification and fiber fabrication techniques developed at NRL.[1] Recently, optical loss in multimode sulfide fiber in the Band I, II and IV regions has been reduced to < 0.5 dB/m

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14. ABSTRACT
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(which corresponds to transmission in the fiber of > 90% in one meter). In addition, mechanical strength in the fibers is such that the fibers can be bent to diameters as small as 1 - 2 cm without breakage.[2] The fibers are of step index design, with numerical aperture (N.A.) of 0.2 to 0.4, depending on choice of compositions for the core and clad. Due to their low loss and high mechanical strength, the chalcogenide fibers are promising as flexible replacements for all-mirror systems currently being fabricated to connect the IR laser to the Jam Head. In addition, we have recently shown successful jamming of missile seekers using Band IV output from these fibers at Sanders (Lockheed-Martin).

In this paper we report on the most recent tests done at Sanders in which the objective was two-fold: to determine the transmission and optical power handling capability of the fibers using Sanders' state-of-the-art, high power optical parametric oscillator (OPO) in the 2 - 5 μm region, and also to observe the smoothness of the beam profile exiting the fiber. These results will be presented below following a brief experimental description.

2.0 EXPERIMENTAL DESCRIPTION

The benchtop laser used in these experiments consisted of a $ZnGeP_2$ OPO crystal pumped by a diode-pumped Ho:YLF laser whose radiation was passed through dual Ho:YLF amplifiers. The laser and fiber setup are depicted in block form in Figure 1. The beamline consisted of radiation from Bands II and IV with the Band I radiation filtered out by BS1 and BS2. Lens L1 was a 6 inch collimating lens. A variable attenuator was used to control the input power level and the beam was focused to a tight waist at the fiber input by L2, a 1 inch focusing lens. The maximum available average power at Bands II and IV as measured after lens L2 was 2.69 W. The repetition rate was 10 kHz and pulsewidth (measured during the tests) was 10 ns; thus the highest energy per pulse was 269 μJ.

To determine the power density incident on the fibers we first had to obtain an accurate measurement of the focused beam radius. With the fiber removed, beam profile data was recorded by a dual slit Photon Beam Scan profiler, mounted on a motorized translation stage which was translated in the z direction (i.e. along the axis of focus). From the Beam Scan profiler data obtained as a function of z, the minimum beam size, equal to the focused beam diameter (at the $1/e^2$ intensity points of the beam profile) was measured to be about 80 microns. This value was confirmed by another experiment in which a knife edge was scanned across the focal plane.

As shown in Figure 1, each fiber, with SMA end terminations, had its input end mounted on an XYZ translation stage in the focal plane of L2 and its output end facing the power meter (Coherent Ultima LM-10). The laser input to fiber alignment was obtained by maximizing transmission through the fiber. The input power, previously calibrated to the power after L2, was measured after reflection from the beam splitter BS2, and the fiber output power was recorded simultaneously. Each fiber was approximately 1 m. in length.

3.0 FIBER TRANSMISSION RESULTS

Fibers were tested which had their endfaces polished in SMA connectors; one of these fibers had anti-reflection (AR) coatings deposited on both endfaces. To meet optimum transmission requirements, the fibers need to have AR coatings, due to the high refractive index (n=2.4) of the glass. We have had AR coatings deposited by an outside vendor which have increased transmission from 58% to 83% as measured at Band IV. With the OPO laser input, we tested the power handling capability of both uncoated and AR coated fibers, with results as described below.

3.1 RESULTS FOR UNCOATED FIBER TRANSMISSION

A total of three different sections of uncoated fiber were tested for transmission using the Bands II and IV output from the OPO laser source. Figure 2 shows transmission results obtained with Fiber R5-1, an uncoated 1 m. section of fiber with 300 μm core diameter. The transmission was about 69% per meter, which agreed with previous measurements of loss of this fiber. The fiber was irradiated for an extended period of time, corresponding to 2.6×10^7 pulses, at the highest input power of 1.6 W. The highest peak power density at the fiber input was 637 MW/cm^2. Upon removal the fiber endfaces showed no evidence of damage when examined with a
200X Buehler Fibrscope (hand-held microscope).

Next a fiber with smaller core diameter was tested. Figure 3 shows the results for transmission through an uncoated fiber with 160 μm core diameter. The tested transmission was about 69% which again agreed with previously measured loss in this fiber. The maximum average power input to this fiber was **2.69 W (26.9 kW of peak power)** for 25 min. total irradiation time. This corresponds to **1.5×10^7 pulses total irradiation at the highest power**. As shown in Figure 4, **there was no change in transmission during this irradiation**, and upon removal of the fiber after the test, no observable change to the fiber endfaces was observed with the Fibrscope.

Results for transmission with the third uncoated fiber, Fiber 208-1, are shown in Figure 5. Due to higher loss in this fiber, the transmission was only about 48%. However the fiber still sustained long term irradiation at high power. The power output was stable for 28 min. (1.7×10^7 pulses) at an input power of 2.6 W. Upon close inspection after testing, a small damage spot was noticed on the fiber input endface. This was later determined to be due to a defect (bubble) in the fiber core which had been very near the surface and was invisible upon initial polishing, but during damage it became visible.

3.2 RESULTS FOR AR COATED FIBER TRANSMISSION

Figure 6 shows the results for tests on AR coated fiber using Bands II and IV input radiation. In run 45A, the output power from the fiber was stable (transmission of about 76%) for input power up to about 300 mW. As the power was increased, the transmission slowly began to decrease. After testing at 1.78 W for about 18 min., where the transmission remained at 68%, the fiber was removed. Upon examination a small damage spot was observed in the fiber coating on the input end. The peak power density at which the damage first occurred was estimated to be 477 MW/cm^2. The fiber was then replaced in the setup with input and output ends reversed. Upon increase of input power, the transmission was again observed to slowly decrease until, after stopping at 1.7 W input, the fiber was removed and the input end was observed to have damage. The cause of the damage is unknown; however the AR coatings were not optimized for this fiber and with improvements in the process higher damage thresholds are anticipated.

4.0 FIBER OUTPUT SPATIAL DISTRIBUTION RESULTS

4.1 THEORY

The output of narrowband laser radiation from a multimode fiber usually exhibits an intensity distribution or speckle pattern of high and low intensity regions. Such a speckle pattern is undesirable for IR countermeasures since it effectively transmits a beam with "holes" in the radiation distribution. This speckle can effectively be smoothed by randomizing the output speckle distribution as a function of time. NRL has used a "dithering technique" in the past,[3] which, by dynamically varying the input angle to the fiber using piezo-driven mirrors, effectively produces a time-averaged superposition of speckle patterns at the output. Alternatively, we can take advantage of the fact that speckle is a function of spectral linewidth of the laser source by employing lasers with wide spectral bandwidths, thus reducing the laser coherence length and resulting in a smooth output beam from the multimode fibers.

The relationships between NA, spectral bandwidth and speckle noise are shown below. In order for the amplitudes of the radiation propagating in the individual modes to add incoherently we want a long mode delay in the fiber. This is a function of index and NA.

Modal Delay:

$$\tau_{md} = \frac{l(NA)^2}{(2 \cdot c \cdot n)} \tag{1}$$

We also would like to reduce the temporal coherence length of the source which is a function of wavelength and spectral bandwidth BW.

Laser Temporal Coherence Length:

$$\tau_c = \frac{\lambda^2}{c \cdot BW} \tag{2}$$

Given these relationships the noise expected in the output of the fiber is:

RMS Amplitude Noise Between Modes:

$$noise_{rms} = \frac{\tau_c}{2\tau_{md}} \quad (3)$$

In the following we discuss the results of beam quality experiments using the OPO employed in the tests, which has a wide spectral bandwidth.

4.2 RESULTS FOR FIBER OUTPUT SPATIAL DISTRIBUTION

The wide spectral bandwidth (≈100 nm) at each of Bands II and IV from the OPO was expected to result in a spatially smooth beam, appropriate for IRCM. The calculated RMS noise from equation (3) was predicted to be 1% or less for a fiber with N.A. = 0.2. The Band I beam had a spectral bandwidth of about 2-3 nm which was expected to result in an order of magnitude greater degree of speckle. The experimental setup at the fiber output consisted of a one-inch focal length, aspherical lens which imaged the near field of the fiber onto a Spiricon infrared camera, from which the image was captured by the laser beam analyzer. Results for Fiber R208-1 are shown in Figure 7(a). As expected, the output distribution for Bands II and IV input radiation were smooth with no discernible minima.

Appropriate filters were then inserted into the beam path to couple only the Band I spectral line into the fiber. Because of the difference in wavelength, the Band I radiation focused to a different spot size and focal position from that at Band IV. Time constraints did not allow us to verify the spot size and location and therefore we were not able to launch radiation efficiently into the fiber. However we were able to obtain the fiber output profile shown in Figure 7(b), which shows evidence of speckle. This is due to the narrow spectral bandwidth at Band I (2-3 nm) and is consistent with theoretical predictions.

5.0 SUMMARY AND CONCLUSIONS

In summary, the chalcogenide fiber transmission tests carried out at Sanders (Lockheed-Martin) were highly successful in that the fibers were capable of transmitting high power for extended times using a state-of-the-art mid-IR laser source designed for IRCM. The following key results were obtained:

- The uncoated fibers were able to tolerate **at least 1.07 GW/cm^2 peak input intensity for up to 1.5 x 10^7 pulses**, with Bands II and IV input. The maximum available peak power at the fiber input was 26.9 kW.
- **Optical damage <u>limits</u> were not determined for the uncoated fiber** at these wavelengths, since *no damage was observed for defect-free fibers*.
- The AR coated fiber sustained damage to the coating at a lower input power density of 477 MW/cm^2. This is believed due to defects in the coating or coating/ fiber interface which should be reduced with optimized coating processes.
- The spatial distribution at the output from the multimode fiber showed **no speckle at Bands II and IV** due to the large spectral bandwidth (> 100 nm) of the OPO laser source, as predicted by theory.

These results will enable the implementation of fiber cable in a variety of IRCM systems, including Multispectral Countermeasures, the Navy TADIRCM system, and the Air Force LIFE system.

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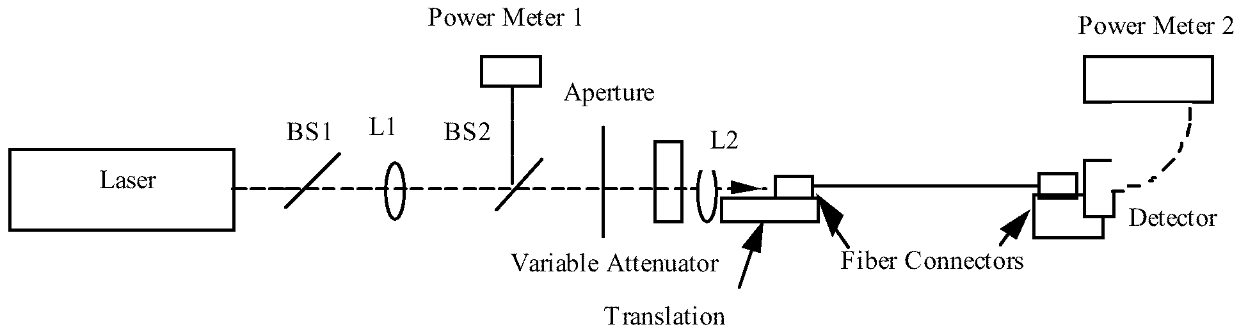

Figure 1: Experimental Setup for Fiber Transmission Tests

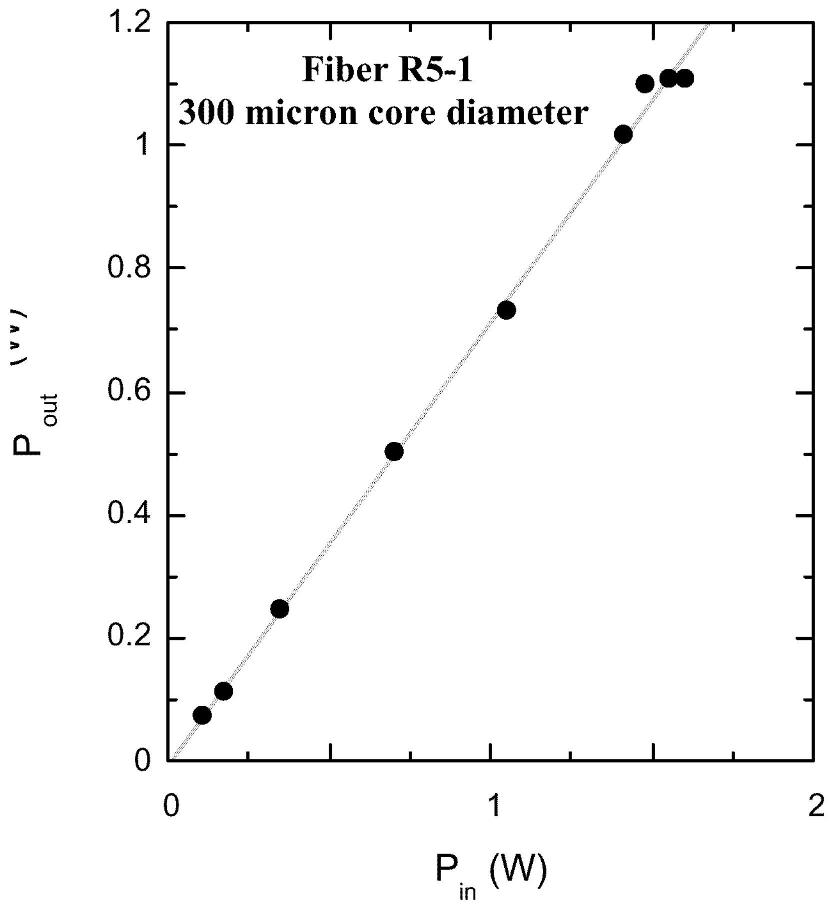

Figure 2: Transmission through 1 m. of Fiber R5-1

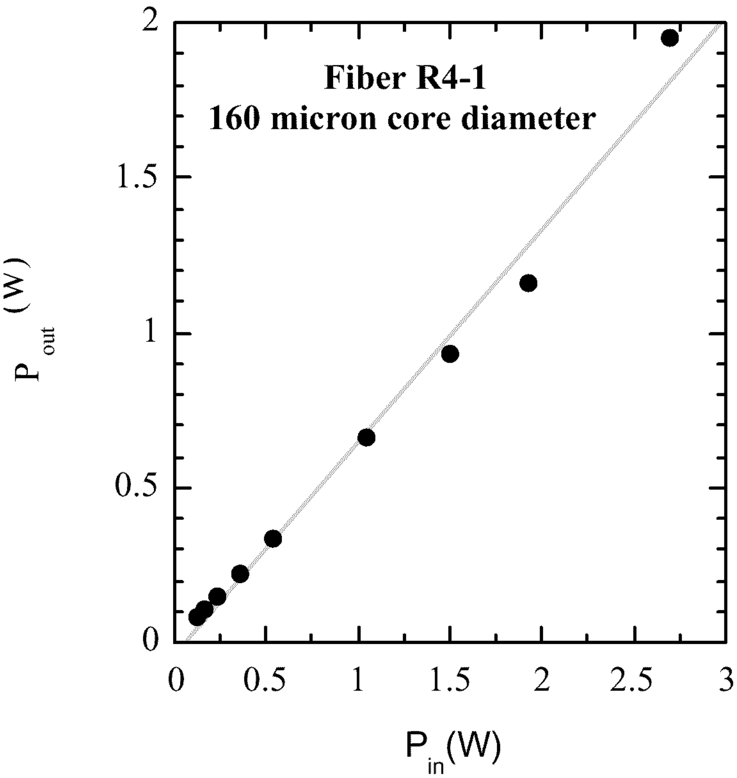

Figure 3: Transmission through 1 m. of Fiber R4-1

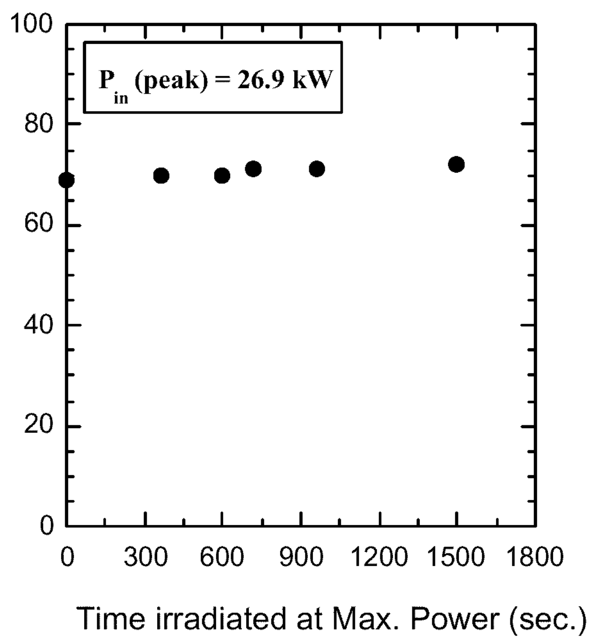

Figure 4: Long time irradiation of Fiber R4-1 at highest input power.
No damage was observed.

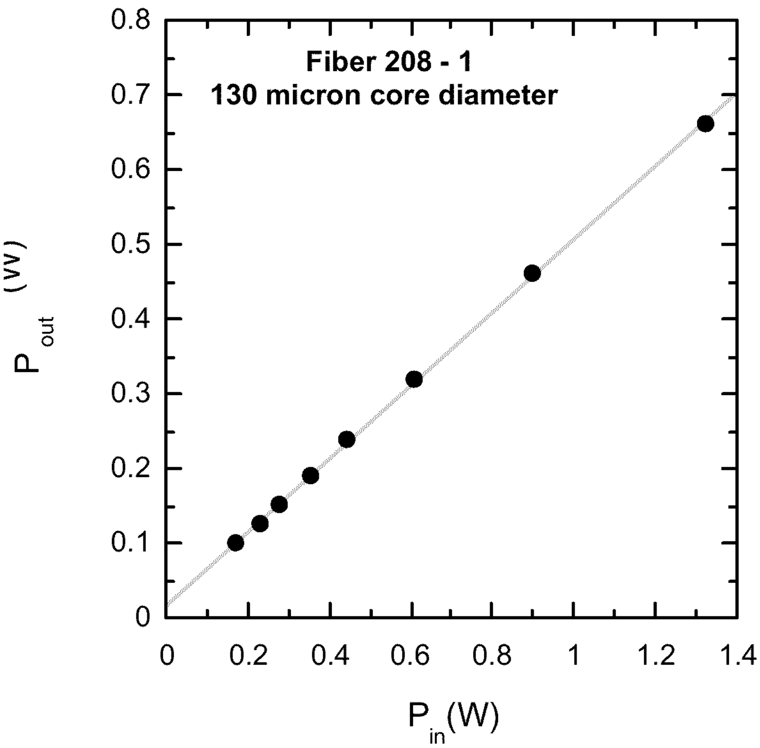

Figure 5: Transmission through 1 m. of Fiber 208-1.

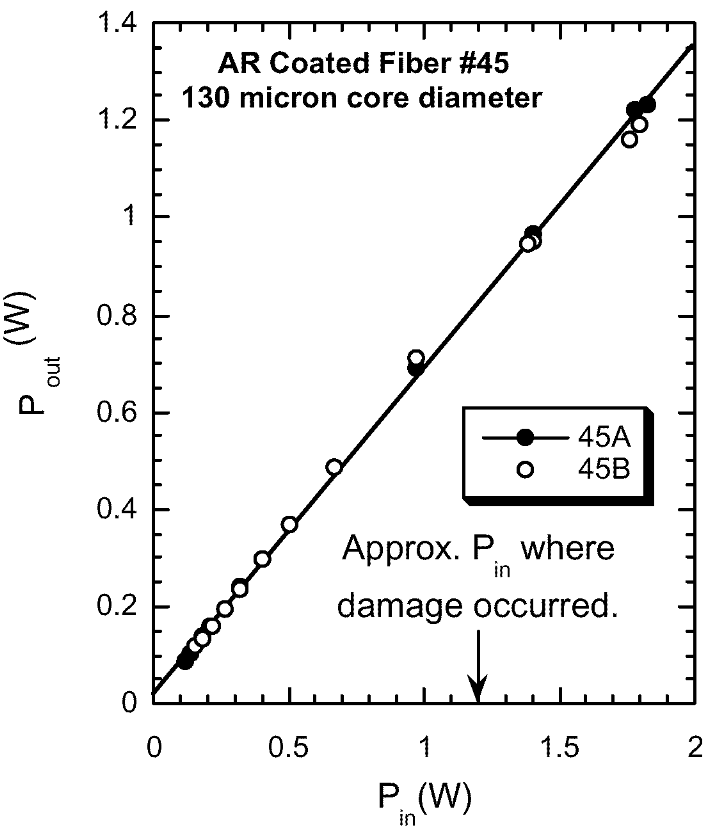

Figure 6: Transmission Tests of AR Coated Fiber #45.

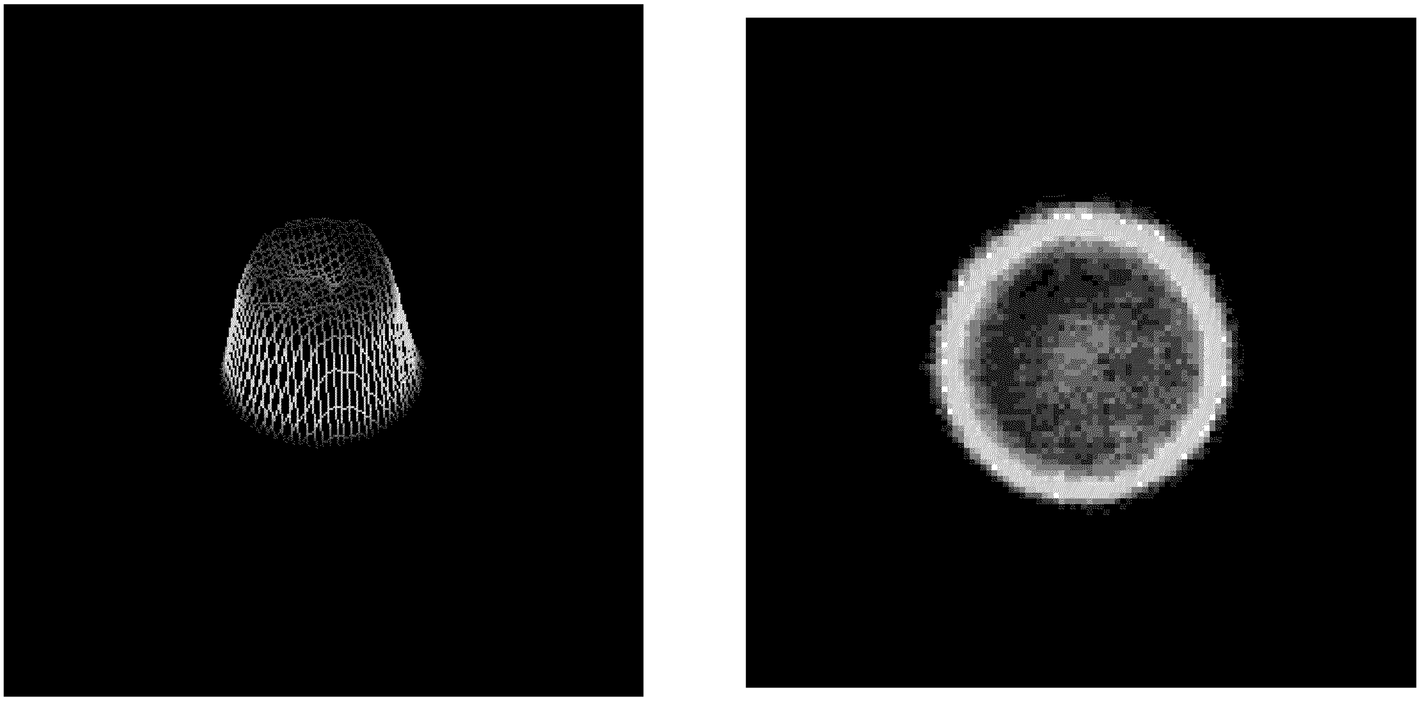

Figure 7(a): Output spatial distribution from Fiber 208-1 (N.A. = 0.29, 130 μm core dia.) showing smooth near field intensity profile for Bands II and IV.

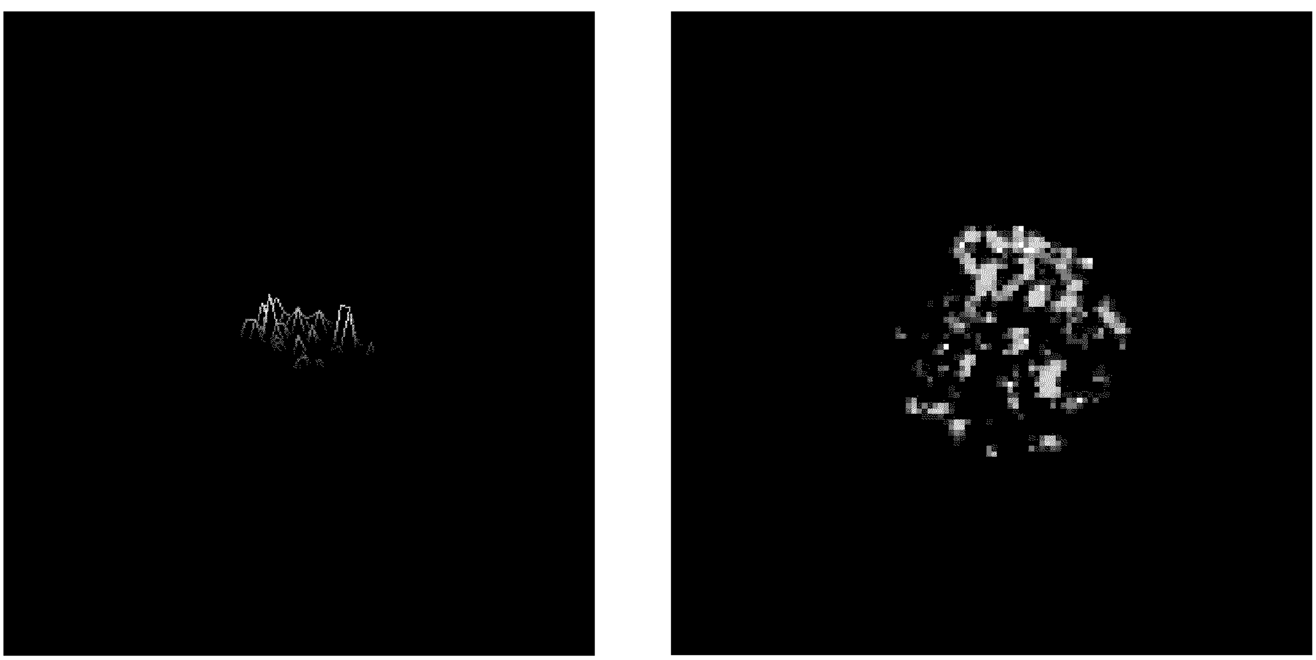

Figure 7(b): Output spatial distribution at Band I for Fiber 208-1 (non-optimum launch).