Beam Cleaning Effect at Amplification of CW Single-Frequency Radiation in Multimode Fiber Taper

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Though singlemode optical fibers remain to be "workhorse" in optical communications and other real-life applications of fiber optics, multimode optical fibers have attracted a lot of interest over the past decade. It comes due to their great potential for new-generation telecom systems with spatial-division multiplexing and multimode fiber lasers with enhanced power, as well as new nonlinear optical phenomena manifesting with the use of high-energy pulsed multimode beams [1,2]. One of these phenomena, spatial self-cleaning is a most intriguing nonlinear effect involving the transformation of a speckled beam into a smooth beam with a bell-shaped profile at the multimode fiber output which is observed above some threshold value of peak power for sub-nanosecond pulses [3]. The effect is usually observed in passive multimode fibers with graded-index (GRIN) profile, but other types of fibers may exhibit similar behavior. For example, in active (Yb-doped) multimode GRIN fiber taper a highly-multimode pulsed output beam observed at low power experiences self-cleaning after amplification to peak power of ∼20 kW with quality parameter M^2 improved from >10 to ∼4 [3,4]. Here we study amplification of a continuous-wave (CW) single-frequency (SF) radiation in similar multimode GRIN fiber taper and observe beam cleaning effect at much lower output power with beam quality improvement to near-Gaussian diffraction-limited beam (M^2<1.5).

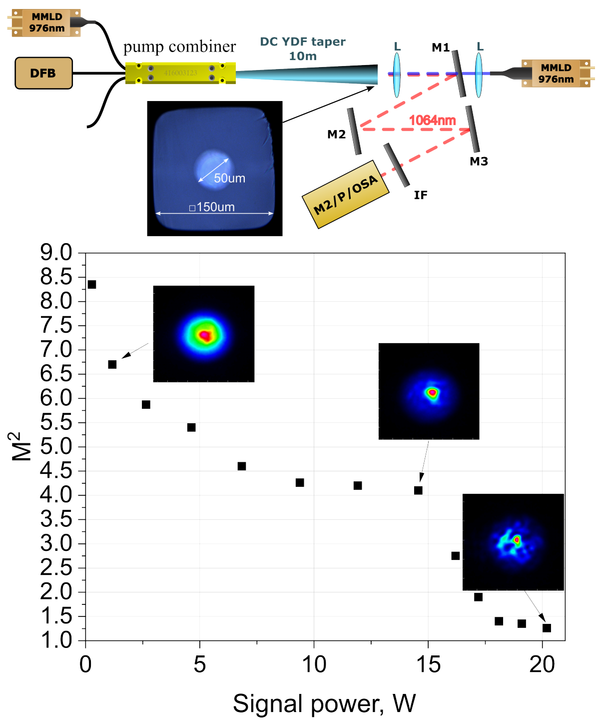

Figure 1: Experimental setup and the measured output beam profile and quality parameter as a function of its power

The performed experiment consisted in amplification of a SF radiation from a DFB fiber laser in a multimode Yb-doped GRIN fiber taper. The DFB laser is implemented in a polarization-maintaining singlemode fiber, its maximum output power was 15 mW at a wavelength of 1064 nm. The output of the seed is coupled to the narrow end of the tapered amplifier via (2+1)×1 pump combiner (see Fig. 1). The tapered fiber was a 10 m long double-clad waveguide with a square cladding and a multimode graded-index circular core. The rib length in the cross section of the narrow end is 100 μm, the core diameter was ∼33 μm, while at the wide end they increase to 150 μm and 50 μm, respectively (see photo in Fig. 1). The amplifier can be pumped from both ends by two multimode laser diodes with a wavelength of 976 nm and an output fiber of 105/125 μm (NA=0.22) through pump combiner or collimating lenses L, respectively. The output end of the amplifier was cleaved at an angle of ∼10^o to reduce Fresnel back reflection. The amplified beam was characterized with the use of dichroic mirrors M1-3 and interference filter IF.

The obtained output power of the amplified signal reaches 20.2 W at the presence of 50 W backward pumping and 15 W forward pumping. Since the amplifier had a core supporting many transverse modes, it is interesting to track how the output beam profile and its quality parameter change with increasing power. The measured profile of output beam has a bright central spot and a weaker halo repeating the cross-section of the core, with the relative intensities depending on power. The corresponding beam quality parameter M^2 calculated from the beam divergence (measured at the intensity level of $1/e^2$). At the measurements we first increased the pump value from the wide end (output signal 0-15 W with pumping 0-50 W), and then added pumping from the narrow end (output signal 15-20 W with additional pumping 0-15 W). At that, the backward pumping improves the beam quality from $\sim$9 to $\sim$4, whereas adding forward pumping leads to further beam cleaning to $M^2<1.5$.

The obtained results depicted in Fig.2 show similar behavior of the output beam quality as that for sub-nanosecond pulses in similar taper amplifier with backward pumping [5]: it is significantly improved (from initial M^2 $\sim$9) with increasing gain/output power to $\sim$10 W and saturates at the level of $\sim$4 at further increase. However, the beam cleaning and its saturation for the amplified CW SF radiation occur at $\sim$3 orders of magnitude lower signal power (10-15 W). Moreover, when we added a forward pumping, the output signal power increases to 20 W while its beam quality is cleaned to level $M^2<1.5$ corresponding to nearly diffraction limited beam. Although some noisy speckled background is visible at the highest power, the main part is conserved in the bright central spot. At the same time, the signal linewidth measured by self-heterodyne method is kept within initial value of about 30 kHz.

So, we demonstrate amplification of CW SF signal to 20 W level in multimode Yb-doped GRIN fiber taper with excellent output beam quality and narrow linewidth which are comparable with that for nearly-singlemode fiber taper [6] but eliminate its sufficient drawback – high sensitivity to fiber bending. To clarify the mechanism of CW SF beam cleaning at such low power level, we perform a mode decomposition in real time [7] and obtain transverse mode distribution of the output beam as a function of signal power. The details will be presented at the conference.

Acknowledgements: The authors acknowledge financial support by the Russian Science Foundation (21-72-30024-П).

References

[1] K Krupa, Alessandro Tonello, A Barthélémy, *et al.*, APL Photonics **18**, 110901 (2019)

[2] L G Wright, F O Wu, Ds N Christodoulides and F W Wise, Nat. Phys. **18**, 1018 (2022)

[3] K Krupa, A Tonello, B M Shalaby, M Fabert, A Barthélémy, G Millot, S Wabnitz and V Couderc, Nat. Photonics **11**, 237 (2017)

[4] A Niang, T Mansuryan, K Krupa, *et al.*, Opt. Express **27**, 24018 (2019)

[5] A Niang, D Modotto, A Tonello, *et al.*, IEEE Photonics J. **12**, 6500308 (2020)

[6] A I Trikshev, A S Kurkov, V B Tsvetkov, S A Filatova, J Kertulla, V Filippov, Yu K Chamorovskiy and O G Okhotnikov, Laser Phys. Lett. **10**, 065101 (2013)

[7] D S Kharenko, A A Revyakin, M D Gervaziev, M Ferraro, F Mangini and S A Babin, Photonics **10**, 1245 (2023)