High-power pulsed fiber lasers for space-based remote sensing

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Specialty fiber and component development may enable long-range laser radar and standoff chemical detection.

Space-based active remote sensing enables applications of significant scientific interest, including topographic mapping and surveying of terrains, and standoff detection of airborne species such as greenhouse gases and chemical process effluents. Laser transmitters for such applications have traditionally consisted of pulsed diode laser pumped solid-state lasers (DPSSLs) relying on bulk crystalline media such as the ubiquitous neodymium-doped yttrium/aluminum garnet and vanadate. Although capable of very high pulse energy, these DPSSLs can incur thermo-optic beam quality (BQ) degradation at high average output powers. They also rest on optical benches that include many free-space components, which can be subject to misalignment and contamination.

Fiber laser sources present distinct benefits over bulk DPSSLs. Among these advantages are excellent BQ (controlled by waveguide design), reduced size, weight, and power consumption (SWaP), and simpler thermal management via both low quantum-defect pumping and a diluted heat load (thanks to the large surface to volume ratio of fiber). They also support architectures comprising minimal or no free-space optical paths.

For broader acceptance of fiber lasers in space-based remote sensing, however, their emitted pulse energy must scale up to values consistent with operation over hundreds of kilometers. Such performance requires us to contain amplified spontaneous emission (ASE) and mitigate in-fiber nonlinear optical effects (NLOEs) to maximize pulse energy and spectral brightness, respectively. Optical damage—a consequence of high optical intensity that manifests itself as a physical rupture in the glass forming the fiber—must also be avoided, as such damage terminates laser operation immediately and irreversibly. Addressing these issues while retaining the primary fiber benefits of low SWaP, good BQ, and an overall rugged build is challenging. Indeed, NLOEs and optical damage can be avoided in large-core fibers with lower optical intensities, but multi-mode

Figure 1. (a) Scheme of a polarization-maintaining (PM) optical-fiber-based master oscillator/power amplifier (MOPA) architecture, featuring all-spliced-fiber frontend followed by a folded rod-type ytterbium-doped photonic crystal fiber (PCF) amplifier. (b) Pulse average power and energy of the MOPA output vs. diode power used for pumping the rod-type PCF final amplifier. Inset: near-field image of output beam at maximum power of ~22W. (c) Temporal profile of emitted pulses. (d) Log-scale, peak-normalized optical spectrum of MOPA output at maximum power of ~22W. Inset: ~5GHz-resolution detail of pulse spectrum. Δν: Frequency difference.

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wave guidance means such fibers usually exhibit poor BQ. Likewise, although ASE is reduced by spectral filters or time-gating components, these methods tend to result in unwanted complexity and larger SWaP.

An example of our efficient pulsed fiber laser source, a master oscillator/power amplifier (MOPA), is shown in Figure 1(a). The MOPA delivers a linearly polarized output centered at 1064nm wavelength with 1.5MW peak power—see Figure 1(b)—and 2.2mJ pulse energy: see Figure 1(c).\(^1\) The device also achieves high spectral brightness: see Figure 1(d). These features demonstrate that our design provides a performance consistent with direct-detection ranging/imaging from low-Earth orbit. The MOPA is seeded by an actively triggered, amplitude-modulated semiconductor laser, which generates low-power pulses ~1.5ns wide at a 10kHz pulse repetition frequency (PRF). These pulses are then amplified by over 60dB in a 975nm-wavelength diode-pumped, ytterbium-doped fiber chain.

ASE power is minimized by arranging the fiber amplifier into multiple stages that are separated by narrow-band spectral filters that reject ASE generated upstream. We reduced NLOEs and reduce optical damage using specialty large-core fibers, which offer lower in-core peak irradiance without sacrificing BQ.

An ytterbium-doped longitudinally tapered fiber (25μm input, 40μm output) and a rod-type PCF with a ~100μm-diameter core,\(^2\) both producing a near-Gaussian beam of M\(^2\) < 1.3, were used as booster and power amplifier, respectively. We specifically suppressed stimulated Brillouin scattering (SBS), which occurs when light interacts with time-dependent optical density variations, by imparting a controlled amount of phase noise to the semiconductor seeder output.\(^3\) The all-fiber nature of its pre- and booster-amplifier stages and the folded layout of the rod-type PCF enabled the MOPA to be compactly packaged to a volume of less than 30cm\(^3\).

Figure 2 provides further examples of pulse-forming agility, high efficiency, and high-peak spectral brightness operation of a fiber-based, 1064nm-wavelength MOPA. This device, which is similar to the one shown in Figure 1, features a 40μm-core PCF as the booster amplifier: see Figure 2(a).\(^2\) Performance was investigated for different pulse durations and PRFs (obtained by adjusting the seeder amplitude-modulation characteristics). We achieved single-frequency, sub-ns pulses of near Fourier-transform quality (<1GHz linewidth) with PRF, energy,

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1. Figure 2. (a) Scheme of PM-fiber-based MOPA architecture: (i) detail of fusion-spliced beam expanding end caps applied to both PCFs. Cross sections of (ii) 40μm-core and (iii) rod-type (100μm-core) PCFs. (b) Example of pulse temporal profiles (top) and corresponding spectrum emitted (bottom) by rod-type PCF. (c) Example of 40μm-core PCF performance: 3ns/1.5MHz duration/pulse repetition frequency (PRF) pulses of >200W average power and single-transverse-mode beam quality (BQ). Near-FT: Near Fourier-transform.

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and peak/average power of 50kHz, 1.1mJ, and 1.35MW/55W, respectively: see Figure 2(b). We were also able to generate SBS-free, spectrally broadened (phase-modulated) pulses of approximately 6GHz linewidth, 4.6ns duration, 2.8mJ energy, and 620kW/56W peak/average power. Finally, we operated the booster PCF amplifier at high PRF (~1.5MHz) and, in this regime, generated optical pulses of approximately 3ns duration with good BQ and an average power in excess of 200W. The amplifier exhibited an optical slope efficiency of 70%, corresponding to an electro-optic efficiency close to 30%: see Figure 2(c).

In summary, our results confirm that fiber-based pulsed lasers/amplifiers are promising optical sources for active, long-range (e.g., space-based) remote sensing. Extensive support for pulse format control (similar to optical telecom transmitters), good BQ, low SWaP, simple thermal management, and an inherently rugged and flexible architecture are among the advantages provided by such a system. Large-core fibers capable of efficiently generating good BQ, including the PCF and longitudinally tapered large-mode-area fibers described, have also enabled substantial power scaling. MOPAs based on these fibers can produce a high spectral brightness output of multi-mJ/MW at peak power/energy and are therefore potentially amenable to laser radar and chemical probing. Our future goals include additional power scaling and spectral brightness for applications requiring longer range and higher detection sensitivity, and generating new temporal/spectral pulse patterns. Developments such as these may involve beam multiplexing techniques\textsuperscript{4,5} and/or innovative solid-state laser architectures that combine fiber and bulk elements.

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References