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Invited Paper

High-power ns-pulse fiber laser sources for remote sensors

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ABSTRACT

The development of fiber-based laser sources for space-borne remote sensors must meet many concurrent requirements including high pulse energy/peak power, excellent beam quality, narrow spectral linewidth, simple thermal management, small volume and mass, low power consumption, rugged packaging, and long-term reliability. To address these requirements, many aspects of pulse fiber laser technology must be advanced beyond the state of the art of traditional optical sources used in telecommunications and materials processing. In this article, we discuss component and solutions that enable pulsed fiber laser sources to support remote sensing from space. We also describe several examples of such sources and characterize their performance.

1. Introduction

Active (i.e. laser-based) remote sensors deployed on satellites offer unique benefits for studies of the earth surface and atmosphere, including support for global and continual coverage regardless of latitude and time of day [1–3]. However, the deployment of laser transmitters in space is challenging because these devices must typically satisfy many requirements at once, including high optical power for long-range operation; high spectral brightness for background light rejection; low size, weight, and power consumption (SWaP) for compatibility with flight platforms; and high reliability for unassisted long-term operation.

Laser sources deployed in space-based sensors have mainly consisted of diode-pumped bulk-crystal (i.e. non-waveguided) solid-state lasers (SSLs) [4–13]. These laser sources usually emit pulse energy up to multi-100 s mJ at low pulse repetition frequency (PRF) of few 10 s of Hz. Higher PRF/average-power operation in bulk SSLs is typically hindered by beam quality (BQ) degradation induced by thermo-optic effects. On the other hand, photon counting sensors operating at high PRF of 10 s to 100 s of kHz can benefit from low-SWaP optical sources emitting pulse energy in the 0.1–1 mJ range, corresponding to average powers of 10 s to 100 s of watt [14–18].

Fiber lasers are well suited to generating high average power while maintaining good BQ for several reasons including their waveguide design and relatively simple thermal management. In typical fiber laser sources, waste heat is kept low by virtue of their high optical efficiency (exceeding 70% in some Yb-doped fiber amplifiers, for example) and can more easily be removed by virtue of the fiber long and thin form factor of large surface/volume ratio. In addition, all-fusion-spliced architectures, in which light remains effectively confined within glass or monolithically built components, are possible. These architectures may provide high reliability and robustness by reducing contamination risks and eliminating the need for alignment-sensitive optical benches, respectively. Moreover, as fibers are very lightweight and can usually be compactly coiled, they are characterized by high optical gain to volume and weight ratios, which further helps reduce the system SWaP. Finally, the high gain supplied by fiber amplifiers enables architectures in which telecom-type, low-power diode lasers are used to initially generate optical pulses, which leads to excellent pulse timing precision and pulse formatting agility.

In this article, we present design principles to be applied in the development of fiber-based lasers sources suitable for space-based remote sensors. In particular, we discuss solutions to mitigate the onset of nonlinear effects (NLEs), which represent the main limitation to pulse energy/peak power scaling in fiber. Several examples of high-power ns-pulse fiber laser sources operating at PRFs of 10 s to 1000 s kHz will also be described.

2. Mitigation of nonlinear effects (NLEs) in ns-pulse fiber lasers

High-power pulse fiber laser sources for remote sensing are typically configured as master-oscillator/power-amplifier (MOPA) architectures, which offer the important advantage of functional separation between pulse forming and amplification.

The master oscillator (MO) is either a low-power Q-switched SSL or a directly/externally amplitude-modulated diode laser. In

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recent years, passively Q-switched microchip lasers have often been used as SSL MOs seeding fiber amplifiers [19–21] owing to their compact form factor and ability to generate short pulses (∼1 ns) at multi-kHz PRF with pulse energy up to 10 s of μJ. In general, however, actively or passively Q-switched SSLs may exhibit large pulse-to-pulse time jitter, modest pulse formatting ability (pulse duration and PRF are either fixed or inter-dependent), and multi-longitudinal mode operation potentially leading to occasional pulse spiking and damage upon amplification. Some of these issues may be addressed by special techniques such as intra-cavity spectral filtering, pulse pumping, and injection seeding, which, however, tend to increase complexity and potentially reduce the ruggedness and reliability of the laser.

Our MO solution of choice is amplitude-modulated diode lasers [22–24]. These lasers naturally support the generation of agile pulse waveforms, in which pulse duration and temporal profile as well as inter-pulse time interval can be dynamically and precisely controlled via electronics on a pulse-to-pulse basis, as demonstrated by their ubiquitous use in optical telecommunication transmitters. In addition, extended-cavity and distributed feedback or Bragg-reflector diode lasers can emit a single-longitudinal mode output, while still being very compact and monolithic. A drawback of diode laser MOs is that their emitted pulse energy is inherently low, typically in the 0.1–1 nJ range. However, this issue can be offset by the large optical-gain/volume ratio in rare-earth-doped fiber amplifiers, which affords the optical amplification of diode MOs to mJ levels, as required by many remote sensing applications, in compliance with low-SWaP constraints of typical flight platforms.

Because the required optical gain is typically in excess of 60 dB, the MO is normally followed by multiple fiber amplifier stages in series. This design permits to include optical isolators and band-pass filters (and/or acousto-optic time-gating modulators) between fiber amplifier stages, to suppress parasitic lasing and remove amplified spontaneous emission (ASE) generated in the time intervals between pulses.

Generating high pulse energy/peak power in fiber-based MOPAs is contingent upon the minimization of NLEs, which set in because of the fiber length and high optical intensity present within the fiber core.

Significant NLE mitigation can be achieved by imposing stringent requirements on the MO and final fiber amplifier. First, the MO must exhibit single-frequency spectral quality, with strong suppression (possibly, exceeding 30–40 dB) of side longitudinal modes. The suppression of side modes helps minimize four-wave mixing (4WM) in the fiber amplifiers, which may otherwise lead to catastrophic spectral broadening, even at wavelengths (e.g. ∼1 μm) corresponding to normal dispersion in fibers [25,26].

In single-frequency/narrow-linewidth MOs, the lowest-threshold NLE is stimulated Brillouin scattering (SBS), which is extremely detrimental in that it generates a backward propagating pulse that may become amplified traveling upstream in the fiber amplifier chain and cause damage. SBS mitigation can be obtained by ensuring that the in-fiber pulsed beam (acting as the SBS pump) exhibit a spectral linewidth of at least several GHz. This can be achieved by modulating the optical phase of the MO-generated seed pulses [27–30].

Fig. 1 illustrates one of our tested solutions for generating single-frequency, spectrally broadened pulses of arbitrary temporal characteristics. It comprises a single-frequency diode laser, phase modulator, and semiconductor optical amplifier (SOA). The diode laser is directly current-modulated to generate relatively long optical pulses of up to ∼100 ns duration. During such pulses, the laser spectrum is typically found to evolve from initially multi-longitudinal (at the leading edge) to stable single-longitudinal mode (in the last 10–20 ns of the pulse). The SOA, operated in pulsed mode, acts as a time-gated amplifier for this final, spectrally stable portion of the pulse, which results in spectrally single-frequency, controlled-shape, pulses of few ns duration [31]. The phase modulator preceding the SOA is driven by a properly timed, deterministic or pseudo-random voltage signal, which permits to frequency-chirp the pulse spectrum to a 3 dB width of up to several 10 s of GHz (see Fig. 1c). For short pulse durations (<1 ns), SBS is also strongly mitigated, regardless of spectral content, primarily due to a greatly reduced spatial overlap between pulses traveling forward in the fiber and corresponding backward-propagating SBS pulses.

Other in-fiber NLEs relevant to the ns-pulse regime include nonlinear phase modulation and stimulated Raman scattering,

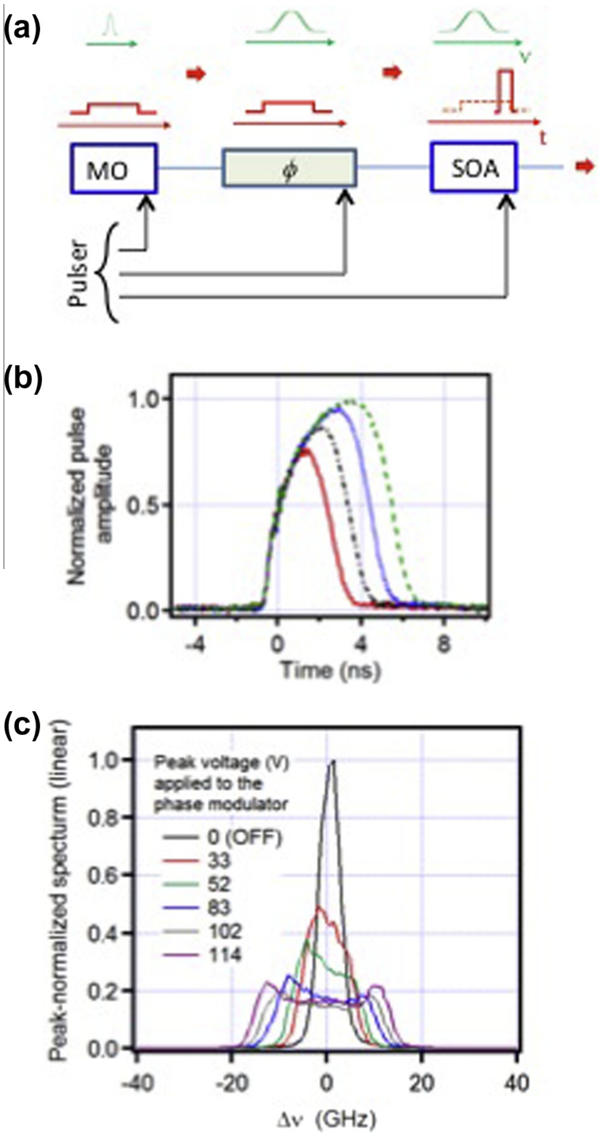

Fig. 1. (a) Architecture of ns-pulse seeder source. MO: Directly modulated, single-frequency diode laser; ϕ: Phase modulator; SOA: Semiconductor optical amplifier. The green and red traces schematically illustrate the function of each active component. Briefly, the MO generates a relatively long pulse, the phase modulator broadens its spectrum to avoid SBS, and the SOA is used as a time-gated amplifier to carve out a spectrally clean portion of the MO pulse. See text for details. (b) Temporal profiles of typical nanosecond pulses emitted by the seeder, recorded with recorded with an InGaAs photo-detector connected to a broadband real-time digital scope, yielding instrument temporal resolution ∼80 ps. (c) Spectra of the seeder emission recorded with a scanning confocal Fabry–Perot spectrometer. For this data, the seeder pulse duration and PRF were set to 5 ns and 100 kHz, respectively. The phase modulator was driven by a deterministic waveform of adjustable peak voltage providing linear chirp. Greater spectral width is obtained by increasing the modulator peak voltage.

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