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NARROW-BANDWIDTH, SUBNANOSECOND, INFRARED PULSE GENERATION IN PPLN PUMPED BY A FIBER AMPLIFIER-MICROCHIP OSCILLATOR (POSTPRINT)

Matthew D. Cocuzzi, Kenneth L. Schepler, and Peter E. Powers

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14. ABSTRACT
Narrow-bandwidth, 0.5 ns IR pulses were achieved in a periodically poled lithium niobate optical parametric generator (PPLN OPG). The OPG was pumped at 7.14 kHz by a Yb-doped fiber amplifier and a microchip Nd:YAG oscillator. Bandwidth was reduced from 3/6 nm to 55 pm using a continuous-wave (CW) 1.5-μm seed beam guided through the fiber amplifier.

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Narrow-Bandwidth, Subnanosecond, Infrared Pulse Generation in PPLN Pumped by a Fiber Amplifier–Microchip Oscillator

Matthew D. Cocuzzi, Kenneth L. Schepler, and Peter E. Powers

***Abstract*—Narrow-bandwidth, 0.5 ns IR pulses were achieved in a periodically poled lithium niobate optical parametric generator (PPLN OPG). The OPG was pumped at 7.14 kHz by a Yb-doped fiber amplifier and a microchip Nd:YAG oscillator. Bandwidth was reduced from 3.6 nm to 55 pm using a continuous-wave (CW) 1.5-μm seed beam guided through the fiber amplifier.**

***Index Terms*—Laser tuning, nonlinear optics, optical fiber amplifiers.**

I. Introduction

PERIODICALLY poled lithium niobate (PPLN) nonlinear devices, such as optical parametric generators (OPGs), have achieved efficient frequency conversion and high peak powers in the mid-IR region, particularly due to the high nonlinearity ($d_{33} = 27\ \mathrm{pm/V}$) [1], noncritical phase matching, and simple fabrication of PPLN. High-peak-power pulsed lasers have been shown to be efficient pump sources for PPLN in the nanosecond and femtosecond regimes [2]–[4], and these sources have been operated in a narrow-bandwidth mode [5]. These PPLN sources have been coupled with compact lasers such as microchip Nd:YAG lasers [6] to make an overall system that is simple and robust. Similarly, robust pump sources include rare-earth-doped fiber lasers, specifically erbium [7], [8] and ytterbium fiber lasers [9], [10], which have been used to pump PPLN and generate tunable mid-IR output.

In this paper, we report efficient generation of 70-pm bandwidth, 0.5 ns pulses in the mid-IR spectral region using OPG in a PPLN crystal pumped by 1064 nm pulses from an Yb-doped fiber amplifier. Our novel device combines the advantages of: 1) using a microchip laser to generate subnanosecond pulses; 2) a robust fiber amplifier for generating significant average power ($>$700 mW); 3) use of simple, single-pass OPG in PPLN for frequency conversion to IR wavelengths; and 4) generation of narrow bandwidth using a low-power seed beam. Previous methods of achieving a short-pulsewidth OPG signal typically relied on large, expensive lasers, active Q-switching, and complex optical resonators. This device uses commercially available, compact, and rugged solid-state components. We have added seeding of the signal beam in the PPLN OPG crystal in a simple and robust manner to achieve narrow-band tunable "eyesafe" 1.5 μm output for spectroscopic applications such as remote sensing. Narrow-bandwidth output was achieved by seeding with a low-power continuous-wave (CW) laser at the signal wavelength using two methods: coaligning the seed beam with the fiber amplifier output before the crystal and guiding the seed beam *through* the fiber amplifier.

This scheme differs from simple modulation of a CW beam because of the high peak powers available. IR signal 1.5 μm pulses with peak powers of 30 kW were achieved. In addition, the PPLN OPG scheme makes high-peak-power idler pulses (2.12–5 μm potentially) available, which are of interest for spectroscopy applications. Additionally, the peak power of the pump pulse was so high that single-pass gain was sufficient to achieve efficient nonlinear conversion, allowing us to use a very simple OPG configuration.

II. Experimental Setup

The oscillator–amplifier laser system [11] used as our OPG pump was built as shown in Fig. 1. The laser oscillator was a Teem Photonics Nd:YAG microchip laser with 1064 nm, linearly polarized, 7.14 kHz repetition rate, passively Q-switched 0.5 ns pulsewidth, 38 mW average power, and 5.3 μJ pulse energy output. The fiber amplifier was pumped at 915 nm using an EM4, Inc., diode laser. The fiber itself was a Yb^{3+}-doped, panda-structure, polarization-maintaining (PM), double-clad fiber manufactured by Liekki and had a 25 μm core diameter and a 248 μm inner cladding diameter. The length of the fiber was 3.56 m. The 915 nm pump power was introduced through the output end of the fiber and the doping was such that 92% of the pump power was absorbed by the fiber. The 1064 nm beam was coupled into the input end of the fiber, as indicated in Fig. 1.

The beam profile characteristics of the 915 nm pump and 1064 nm microchip laser output were measured using the knife-edge technique. This, in turn, enabled us to mode-match both the 915 nm pump and 1064 nm oscillator beams into the fiber. The 1064 nm beam-to-fiber-core coupling efficiency was 55% and the pump beam coupling efficiency was 96%. Damage occurred at 21 $\mathrm{GW/cm}^2$ peak power at the fiber output surface.

Damage was prevented by splicing 400 μm core diameter pure-silica fiber end caps to each end of the fiber [12], [13].

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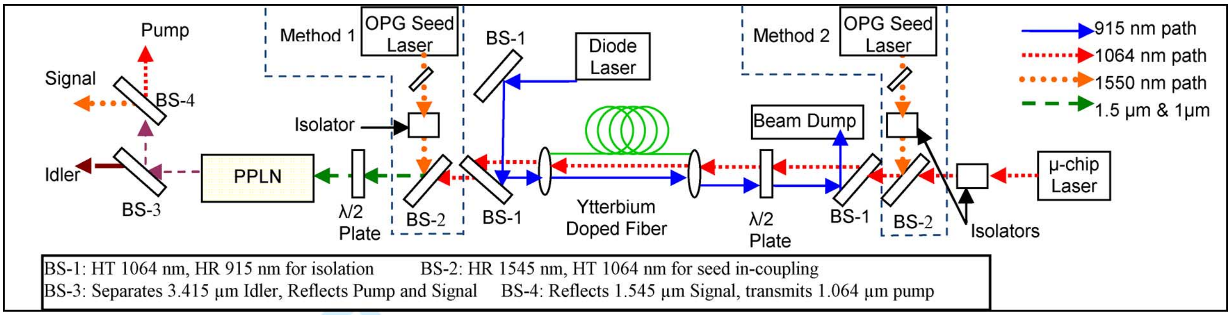

Fig. 1. Fiber amplifier pumped PPLN OPG setup—microchip oscillator laser pulses at 1064 nm are amplified in an Yb-doped, polarization maintaining fiber. The fiber amplifier is pumped by a 915 nm diode laser. Method 1: the fiber amplifier output is combined with the OPG seed beam and pumps a PPLN OPG. Method 2: the OPG seed beam couples into and is guided by the fiber amplifier.

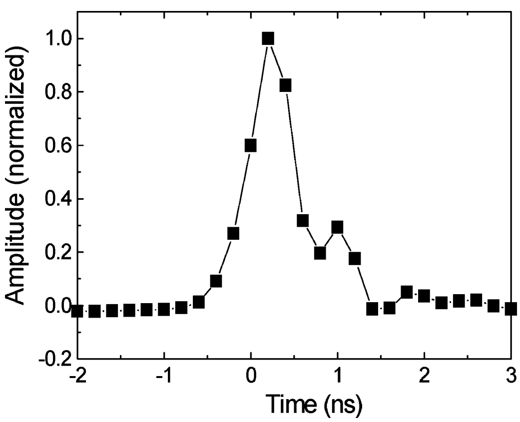

Fig. 2. Fiber amplifier output pulsewidth as measured by a LeCroy WaveRunner 204Xi oscilloscope.

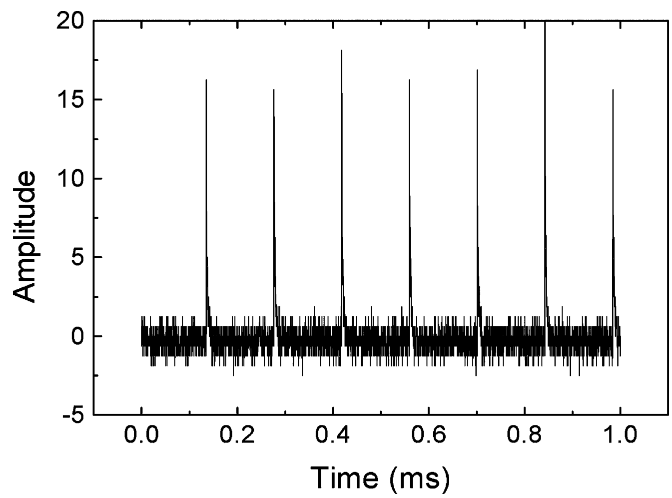

Fig. 3. Fiber amplifier output pulse train.

This reduced intensity at the end-cap surface to $50\ \mathrm{MW/cm^2}$, a factor of 425 below the damage threshold. A maximum output power of 710 mW was achieved at 6.5 W of pump power and 20 mW of microchip oscillator power coupled into the fiber. The fiber output pulsewidth was 0.5 ns, the same as the input laser pulsewidth. The 1064 nm fiber output beam quality was measured to be $M^2 = 1.5$ on the *x*-axis and $M^2 = 1.4$ on the *y*-axis. The fiber output pulsewidth of 0.5 ns and pulse train (7.14 kHz) are shown in Figs. 2 and 3, respectively. The pulse temporal profile was directly measured with a 2 GHz LeCroy WaveRunner 204Xi oscilloscope. The secondary pulse slightly delayed from the main pulse is a common effect in microchip lasers as observed by Schrader *et al*. [14].

The 1064 nm output of the fiber was loosely focused with the same lens used to mode-match the 915 nm pump laser into the fiber. A dichroic beam splitter was used to couple the 1064 nm amplified beam output and the 915 nm pump beam into the fiber amplifier. An 8.8 cm-focal-length lens was used to focus the 1064 nm beam to an 88 μm beam waist (1/*e* field radius) 14 cm away from the lens where a PPLN crystal was mounted on a five-axis stage (three translations, rotation, and tilt). The beam waist was chosen to be 88 μm at the center of the crystal, near the optimum calculated by using the Rayleigh range criterion for maximum gain through the crystal. The PPLN crystal had a 1 mm $\times$ 14 mm cross section and a 49 mm length along the beam propagation direction. Multiple grating periods were poled into the crystal and it was uncoated with approximately parallel front and back surfaces. The domain grating period used was 30 μm, which corresponds to expected 1.545 μm signal and 3.415 μm idler wavelengths based upon $\mathrm{LiNbO_3}$ Sellmeier equations [15]. A half-wave plate was used to rotate the fiber laser output polarization to align with the *z*-axis in the PPLN crystal, hence maximizing nonlinear gain by employing the full magnitude of the d_{33} nonlinear component. The PPLN output was separated by two dichroic mirrors to isolate the signal and idler, as shown in Fig. 1.

III. PPLN OPG PERFORMANCE

A. *OPG Unseeded Performance*

Fig. 4 shows the average power of the signal and idler beams (and total power) with respect to fiber laser output power for unseeded operation—no change in signal or idler powers was observed when the system was seeded. Fig. 5 shows the total conversion efficiency with respect to fiber laser output power.

The nonseeded signal beam reached a maximum output of 107 mW (15 μJ per pulse) at a maximum fiber amplifier output of 635 mW, equivalent to 29% conversion efficiency, with a central wavelength of 1.545 μm and 3.6 nm full-width at

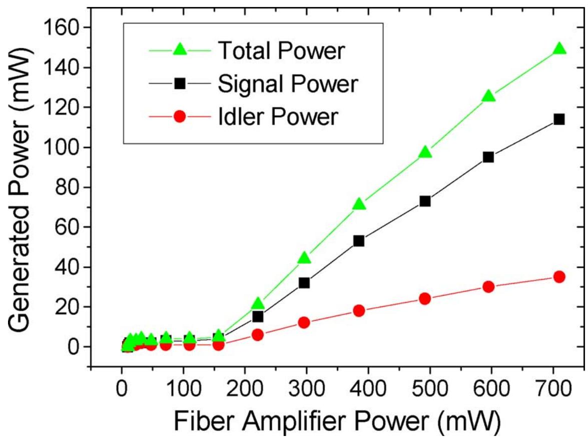

Fig. 4. Signal (1545 nm), idler (3418 nm), and total output power in a 1064 nm pumped, PPLN OPG (solid lines do not represent a physical model).

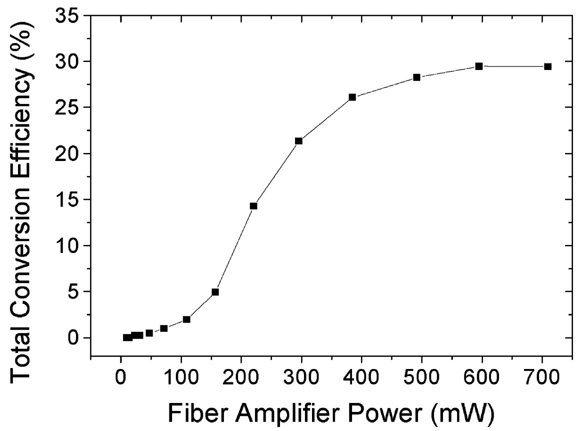

Fig. 5. Total conversion efficiency of pump laser power to OPG signal and idler wavelengths (solid lines do not represent a physical model).

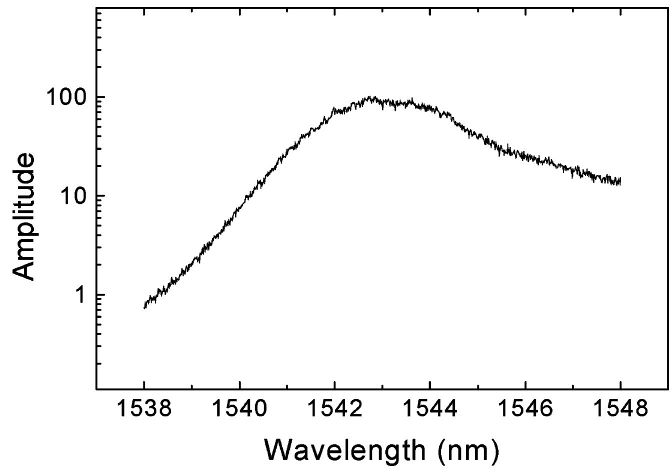

Fig. 6. Unseeded OPG signal spectrum.

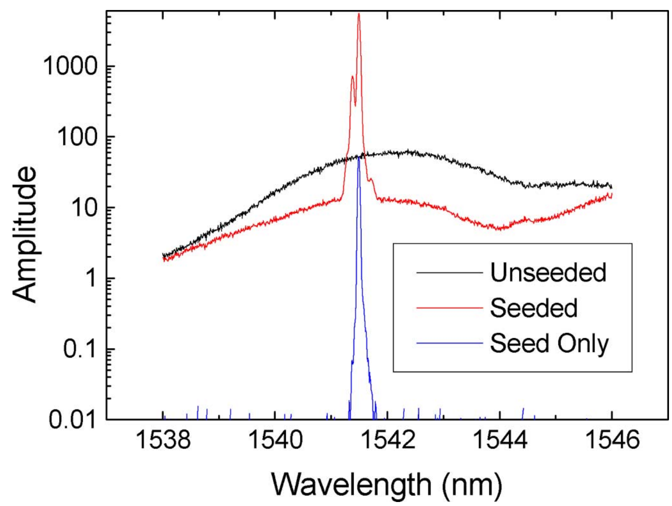

Fig. 7. Unseeded, seeded, and seed-only plots for Method 1 seeding at 4.75 W pump power applied to the fiber amplifier.

half-maximum (FWHM) bandwidth, as measured by an Ando AQ-6315B optical spectrum analyzer (OSA) and shown in Fig. 6. The idler reached a maximum of 37 mW (5.2 μJ per pulse).

B. Seeded OPG Performance

A tunable diode laser with a measured bandwidth of 40 pm (monochromator resolution limit at 10 μm slit widths verified by OSA) was used to seed the PPLN OPG process at the 1.5 μm signal wavelength using two different methods. A 1.55 μm isolator was used in both methods to prevent back reflections and a dichroic mirror was used to protect the diode seed laser from 1064 nm pulses, as shown in Fig. 1. The tunable diode laser power was measured at multiple operating currents and found to have consistent output power at all wavelengths for a given operating current.

In the first method of seeding (Method 1), the OPG seed beam was combined with the 1.064 μm beam after the fiber amplifier output using a dichroic mirror, seeding the OPG with 1.5 mW of seed power. Lenses were used prior to combining the seed beam with the fiber amplifier output such that the seed beam would approximately focus to a 109 μm waist at the center of the crystal, based on the Rayleigh range as had been done for the fiber amplifier output. Shown in Fig. 7 are the seeded, unseeded, and seed-only spectra using Method 1 seeding. Signal beam seeding using Method 1 successfully achieved narrow-bandwidth operation for all fiber amplifier pump powers above 3.5 W and over a seed beam range of 1.540–1.546 μm, as shown in Fig. 8, with an optimal seed wavelength of 1.5435 μm resulting in a bandwidth of 0.055 nm, a bandwidth reduction factor of 65. We note that this bandwidth is within an order of magnitude of the transform limit (7 pm or 0.9 GHz) for a 0.5 ns pulse. Shown in Fig. 9 is the seeding effectiveness measured as the fraction of signal energy in the seeded peak compared to the total signal energy. For Method 1 seeding, the minimum signal seed power required to achieve successful seeding was 130 μW, where successful seeding is defined by the seeded spectrum baseline being attenuated 3 dB below the unseeded spectrum.

For Method 2 seeding, the OPG seed was focused into the input end of the amplifier fiber and guided by the fiber, thus achieving automatic coalignment with the 1064 nm oscillator beam in the OPG crystal. Efficient coupling of the seed beam

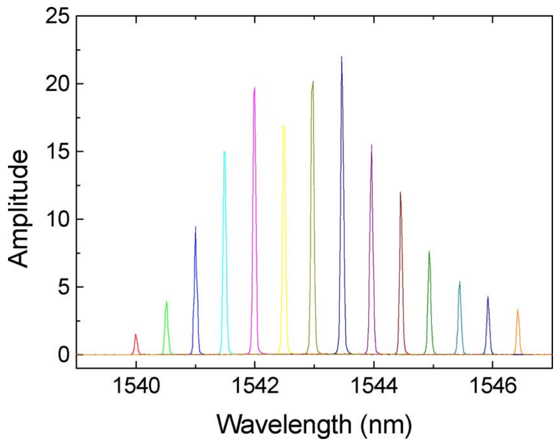

Fig. 8. Wavelength tunability for Method 1 seeding.

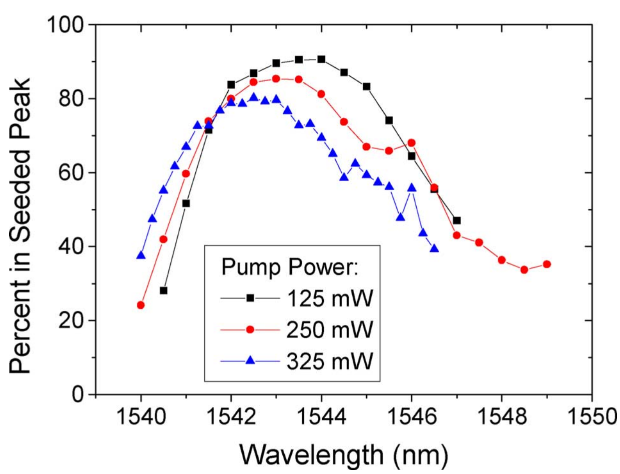

Fig. 9. OPG seeding effectiveness with seed wavelength tuning and changes in 1064 nm pump power for Method 1 seeding.

into the fiber core proved to be difficult. We noted significant seed beam in the cladding as well as in the core of the amplifier fiber. This may have been caused by seed beam polarization components not parallel to the required polarization orientation of the PM fiber, as the 1.54 μm seed beam passed through a half-wave plate designed for 1.064 μm. Seed power of 60 μW was incident on the OPG crystal. Fig. 10 shows the seed beam, unseeded spectrum, and seeded spectrum—note that the seed beam is significantly weaker than as measured in Method 1. Guiding the seed beam through the fiber successfully seeded at a seed wavelength range of 1.541–1.547 μm; wavelength tunability is shown in Fig. 11. The seeded beam bandwidth was measured to be 0.055 nm, a factor of 65 reduction from the 3.6 nm unseeded spectrum. Ideal seeding occurred at a seed wavelength of 1.543 μm, with a minimum power of 30 μW required for successful seeding. Shown in Fig. 12 is a comparison of the percentage of total signal energy in the seeded peak versus the seed wavelength, all measured with maximum seed power.

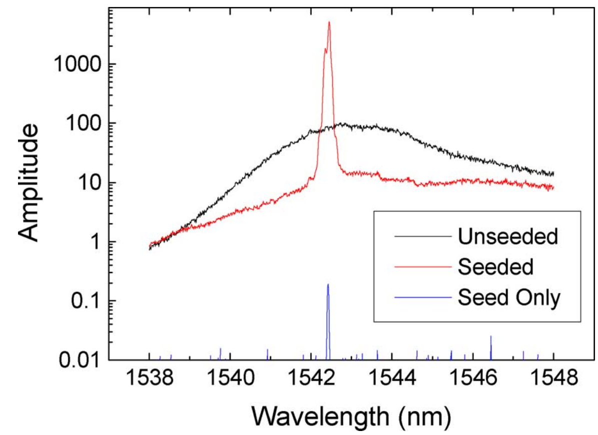

Fig. 10. Unseeded, seeded, and seed-only plot for Method 2 seeding with 4.75 W pump power applied to the fiber amplifier.

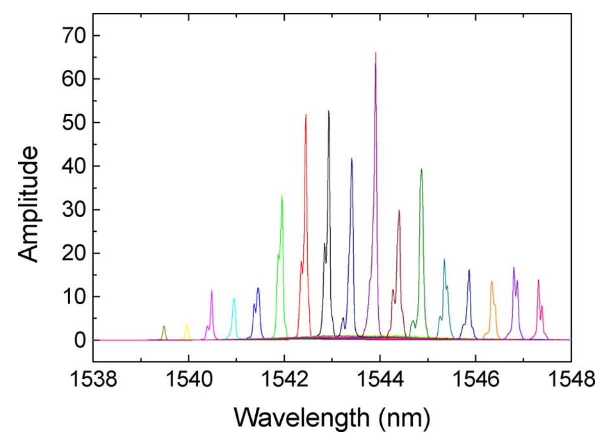

Fig. 11. Wavelength tunability of Method 2 seeding.

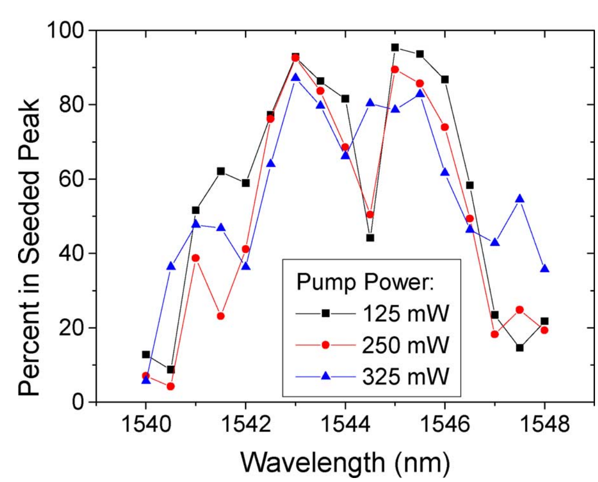

Fig. 12. Seeding effectiveness with seed wavelength tuning and changes in 1064 nm pump power for Method 2 seeding.

IV. Conclusion

We have successfully seeded narrow-band OPG in a PPLN crystal pumped by 0.5 ns pulses generated in a fiber amplifier by introducing a 1.5 μm seed beam between the fiber amplifier output and the PPLN crystal and by guiding the seed beam *through* the fiber amplifier. The polarization maintaining Yb fiber amplifier generated 710 mW of average pump power from 20 mW of injected pulses produced by a microchip laser. OPG signal beam conversion efficiencies as high as 29% were achieved. The relatively large unseeded 3.6 nm OPG signal bandwidth was improved to 55 pm with seeding.

Method 1 seeding after the fiber is reliable, the amount of energy in the seeded peak is very consistent across the signal spectrum, and is optimal for providing maximum seed beam power to the crystal. However, Method 1 requires optics to guide and coalign the seed beam with the PPLN pump beam (in our case, the fiber amplifier output), which can attenuate the PPLN pump. With Method 2 seeding before the fiber, the seed beam is automatically aligned with the fiber amplifier output, though coupling the seed beam into the fiber amplifier required as many optics as coalignment in Method 1. Additionally, Method 2 seeding displayed an unexpected amount of variation in seeding efficiency over the unseeded signal spectrum. This could be a result of destructive interference, losses at particular wavelengths as a result of fiber spooling, or nonoptimal coupling into the fiber core.

Performance factors between Method 1 and Method 2 are similar—bandwidth reduction, seed wavelength tunability, and the amount of energy in the seeded peak—though Method 1 is slightly superior. Method 1 is simpler to introduce after a system has been established, but Method 2 is automatically perfectly aligned with the fiber output.

The device was simple to align and quite stable during operation. The complete device could easily be packaged into a rugged device ideal for eyesafe, high-resolution laser ranging, and remote sensing.

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