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Wavelength-agile fiber laser using group-velocity dispersion of pulsed super-continua and application to broadband absorption spectroscopy

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ABSTRACT A swept-wavelength source is created by connecting four elements in series: a femtosecond fiber laser at 1.56 μm, a non-linear fiber, a dispersive fiber and a tunable spectral bandpass filter. The 1.56-μm pulses are converted to super-continuum (1.1–2.2 μm) pulses by the non-linear fiber, and these broadband pulses are stretched and arranged into wavelength scans by the dispersive fiber. The tunable bandpass filter is used to select a portion of the super-continuum as a scan-wavelength output. A variety of scan characteristics are possible using this approach. As an example, an output with an effective linewidth of approximately 1 cm^{-1} is scanned from 1350–1550 nm every 20 ns. Compared to previous scanning benchmarks of approximately 1 nm/μs, such broad, rapid scans offer new capabilities: a gas sensing application is demonstrated by monitoring absorption bands of H_2O, CO_2, C_2H_2 and C_2H_6O at a pressure of 10 bar.

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1 Introduction

Lasers that can rapidly scan through a broad wavelength range are useful for test and measurement [1], for advanced communications components [2] and for a variety of sensors. Sensing applications include embedded sensors for temperature and strain [3], on-chip biological diagnostics [4] and spectroscopic sensors for gas properties [5, 6]. In most cases, the broadest possible wavelength coverage is desired for flexibility and access to the maximum amount of information. Typically, the scanning is accomplished by sweeping a single laser mode through a significant fraction of the laser gain medium. In this approach, the bandwidth of the gain medium limits the tuning range, and the time response of the thermal [5], micro-mechanical [7] or monolithic [2] mode-sweeping mechanism places an upper limit on the tuning rate. Tuning rates exceeding 1 nm/μs have been demonstrated [6].

This paper demonstrates an alternative approach to achieving rapid wavelength sweeps. Instead of scanning a single mode through a range of wavelengths, the entire wavelength range is generated in a short, broadband pulse. This pulse is then sent through a medium with high group-velocity dispersion (GVD) such as a long optical fiber, so that a wavelength scan emerges from the fiber. The spectral breadth of such scans can be much greater than the gain bandwidth of a single laser, as in the case of the super-continuum described below. The dispersive element limits the tuning rate, but it is a lower limit instead of an upper limit (fast scans are practical but slow scans are not). Typical scans cover 200 nm in 20 ns, which is roughly 10 000 times more agile than previous techniques.

2 Experimental

Figure 1 shows a schematic of the swept-wavelength source configured to scan 1350–1550 nm every 20 ns. The Er-doped fiber laser (IMRA Femtolite) provides 300-fs pulses of 1.56-μm light at a repetition rate of 48 MHz, as shown in inset (a). These pulses are coupled into a polarization-maintaining highly non-linear dispersion-shifted fiber (PM-HN-DSF; IMRA – continuum option) to generate broadband super-continua as demonstrated previously [8] and shown in inset (b). Non-linear processes such as self-phase modulation, four-photon mixing and stimulated Raman scattering act in concert to generate the super-continua. A portion of the super-continuum is shown shaded to represent the sub-spectrum that will be selected by the downstream optics and ultimately delivered as the scan-wavelength output.

The broadband pulses are arranged into wavelength scans by a 5.55-km length of standard dispersion-shifted fiber (Corning MetroCor™). The intensity and wavelength histories corresponding to the selected sub-spectrum are shown as solid lines in inset (c). The fiber's dispersion increases from −122 ps/nm at the blue end of the sub-spectrum to −35 ps/nm at the red end, causing the wavelength to scan as a non-linear function of time. Note that the scan extending outside the selected sub-spectrum (shown dotted) would be complicated by the fiber's zero-dispersion wavelength and single-mode cutoff.

The fiber output is collimated into free space using an (achromatic) off-axis parabolic mirror. The beam is sent to a tunable bandpass filter composed of a grating and a spherical mirror separated by the mirror's 122 cm radius-of-curvature. The 600 g/mm grating spatially disperses the light into a horizontal plane, and the 20-cm diameter mirror retro-reflects the desired sub-spectrum

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to a spot just above the input spot on the grating. The second diffraction at the grating then re-creates a collimated beam just above the input beam; a mirror directs this final output beam to the end use. This filter achieves a nearly perfect "top-hat" passband at the cost of two diffraction-efficiency losses. The filter's passband can be continuously adjusted by rotating the grating and repositioning the knife edge. For large changes in passband width, the grating can be replaced with one of different resolving power.

The output of the wavelength-agile source is used to measure the absorption spectra of high-pressure gases using techniques described previously [5]. In brief, the beam is split into two equal-length paths, one of which contains a 184-cm gas cell, and the two channels are monitored in real-time by balanced 1-GHz detectors. The analog division of the two intensities, which is reduced to the absorption spectrum by Beer's law, is digitized at 20 Gs/s. The balanced detection system minimizes the effects of the large intensity dynamic range seen in Fig. 1c as well as shot-to-shot variations in the non-linear fiber output.

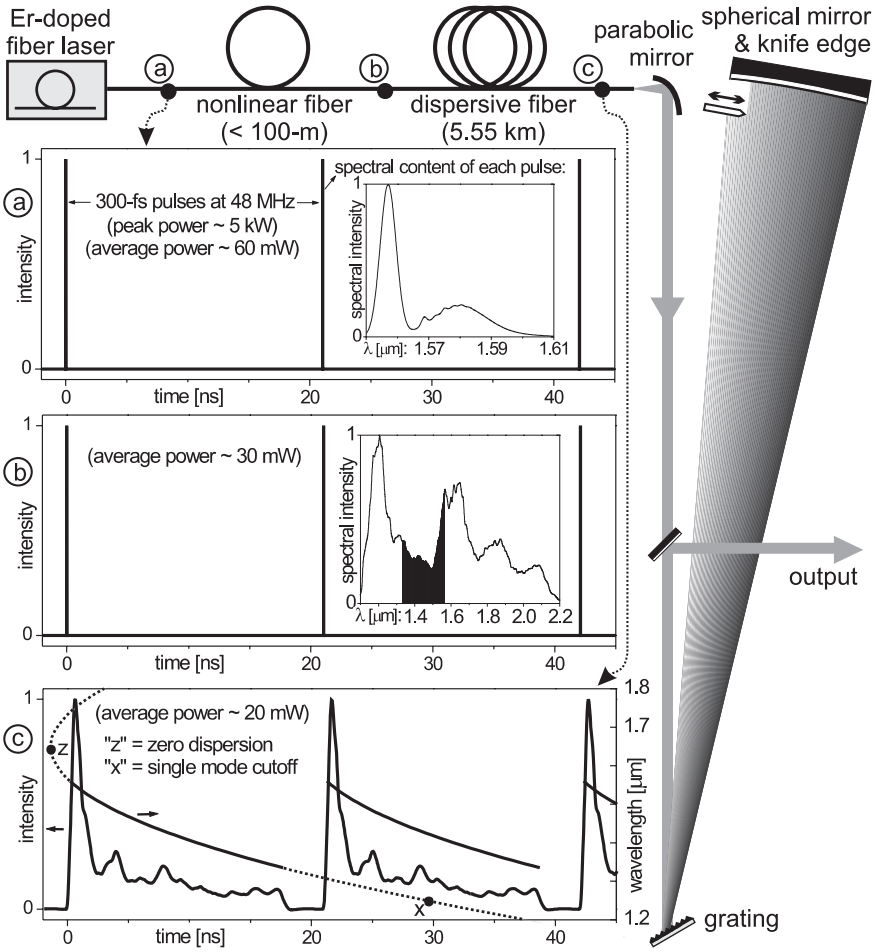

FIGURE 1 Schematic of the wavelength-agile source configured to scan 1350–1550 nm every 20 ns, including performance data measured at locations (a), (b) and (c)

3 Results and discussion

Absorption spectra measured in approximately 20-μs total time by averaging 1000 consecutive scans are shown in Fig. 2. The Fig. 2a results correspond to a mixture of H_2O, CO_2 and C_2H_2 at 10-bar total pressure. Because these gases contain features as narrow as 1.5 cm^{-1} (~ 0.3 nm) at this pressure and the scanning light has a linewidth of approximately 1 cm^{-1}, the optical signals contain a high-frequency absorbance structure that is filtered away by the 1-GHz detectors. This structure could be recovered in this measurement, if desired, using detectors and sampling oscilloscopes with bandwidths of approximately 25 GHz or greater [9]. In addition, the effective linewidth of the scanning light could be reduced as described below, enabling higher-resolution measurements. Because the C_2H_6O (ethanol) shown in Fig. 2b is essentially a "broadband" absorber at 10 bar, little additional structure would be captured in

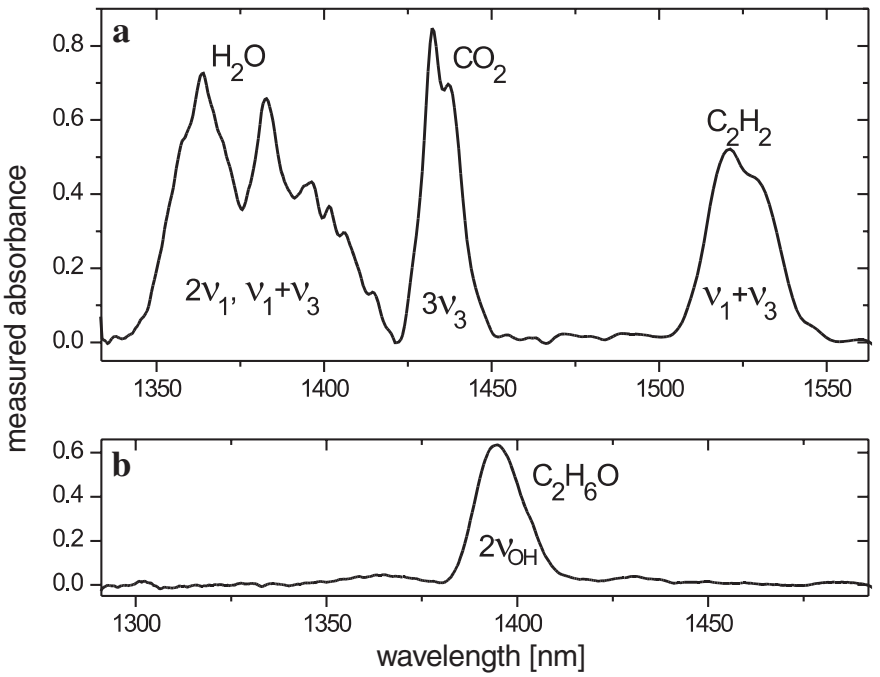

FIGURE 2 Spectra measured in a 184-cm-long cell at $T = 330$ K, $P = 10$ bar. Gas composition: **a** $X_{H2O} = 0.005$, $X_{CO2} = 0.99$, $X_{C2H2} = 0.005$; and **b** $X_{C2H6O} = 0.01$ and $X_{N2} = 0.99$. Note that the tunable filter was adjusted to access a different wavelength range in **b**

this spectrum by increasing the detector bandwidth.

The ability to record such broad spectral information is generally useful, and the ability to record it quickly is particularly useful in transient sensing applications. For example, extending previous work [5, 6], H_2O and fuel absorption bands can now be recorded at MHz rates in unsteady environments such as internal combustion engines. From these absorption bands, gas properties such as temperature, pressure and absorber concentrations can be inferred in real time. Furthermore, the spectral breadth of the sweeps is sufficient for rapid measurements of liquid, solid, aerosol and particulate properties in a wide range of applications.

The source can be configured to provide wavelength scans with various traits, but the dispersive element limits the flexibility of the system. Most importantly, its maximum dispersion (ns/nm) defines the minimum achievable scan rate (nm/ns). For example, in a single-mode fiber, high dispersion comes at the cost of high attenuation; if 10 dB attenuation is allowed, the minimum scan rate for standard and dispersion-shifted fiber is as shown in Fig. 3. The minimum scan rate remains relatively flat throughout the visible because high dispersion offsets the high attenuation. Note that in the 1300–1650 nm range, dispersion-compensating fibers have been well developed and can outperform the fibers shown in Fig. 3, providing scan rates of approximately 0.5 nm/ns at 10 dB attenuation.

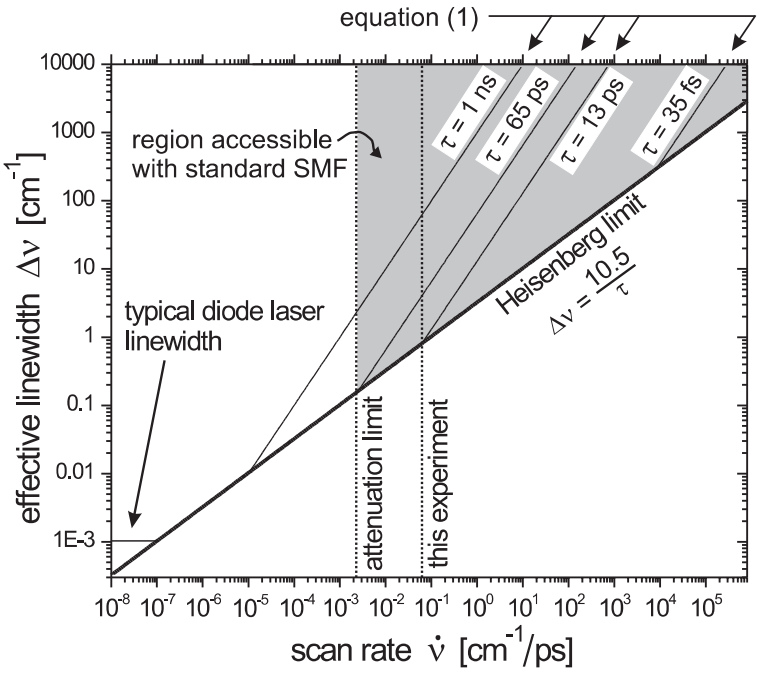

FIGURE 4 Calculated line-widths for sech^2-shaped white pulses dispersed to form wavelength scans

The dispersive element also determines the linearity of the wavelength scans; flat dispersion causes the scanning wavelength to be a linear function of time. A combination of dispersion-compensating and standard fibers can be used to achieve extremely linear scans when necessary – more linear than is possible in the swept-laser-mode approach because of "accelerations" associated with scan reversal at the endpoints.

Finally, the dispersive element affects the linewidth of the scanning light. A simple analysis suggests that the effective FWHM linewidth $\Delta\nu\,[\mathrm{cm}^{-1}]$ is given by:

$$\Delta\nu = \tau\dot{\nu} \tag{1}$$

where τ[ps] is the FWHM temporal width of the input pulse (assumed sech^2 in shape) and $\dot{\nu}$[cm^{-1}/ps] is the scan rate (fixed by the dispersive element). However, as illustrated in Fig. 4, the Heisenberg uncertainty principle can force the linewidth to be broader than that predicted by (1). Reducing the scan rate always reduces the linewidth, but reducing the pulsewidth only reduces the linewidth until the Heisenberg limit is reached. A minimum linewidth of approximately 0.1 cm^{-1} is achievable at the approximate attenuation limit for standard single-mode fiber. Note that the Heisenberg limit shown in Fig. 4 also applies to scanning single-mode lasers and can be relevant for very-narrow-linewidth or rapid-scanning lasers.

In future realizations, components of the scan-wavelength source can be juxtaposed and modified as applications dictate. The dispersive element, tunable filter and absorption cell can be arranged in any order. Multimode, graded-index fibers can be used [10] to accommodate poorly collimated light or light from extended sources. Other dispersive elements can be used in place of long fibers. For example, chirped-fiber

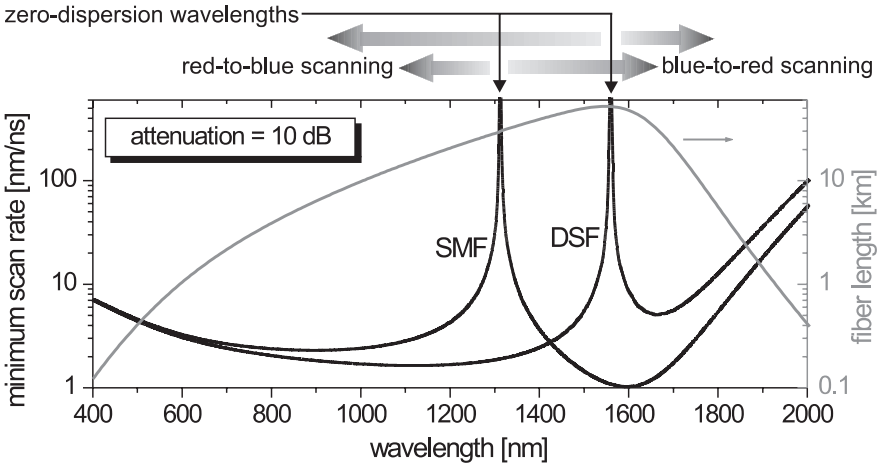

FIGURE 3 Calculated scan-rate limits for typical single-mode and dispersion-shifted fiber. Plot assumes the fiber length and core diameter vary to maintain 10-dB attenuation and single-mode operation

Bragg gratings [11], free-space grating pairs [12] and atomic vapor cells [13] all offer the potential for very high dispersion over a limited wavelength range, and are attractive options in wavelength regions where fiber attenuation is high (e.g. in the ultraviolet). In addition, other pulsed broadband sources can replace the super-continua described here. Fiber-pigtailed edge-emitting and super-luminescent light-emitting diodes are inexpensive and compact alternatives, offering approximately 40-nm-wide, 1-ns-long pulses with peak powers up to 100 mW. The tunable filter can be modified or eliminated when size is a concern. If necessary, fiber amplifiers can be used to boost the power of the scan-wavelength output. Because such adaptations are easily made, one wavelength-agile source can be reconfigured for use in many applications.

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