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Wavelength-agile laser system based on soliton self-shift and its application for broadband spectroscopy

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ABSTRACT A novel laser system for rapid-wavelength scanning applications was developed. The wavelength-tuning mechanism is the soliton self-shift of femtosecond pulses in optical fiber. Increased coupling into the fiber causes an increased wavelength red-shift within the fiber. By varying the coupling efficiency, we can generate rapid wavelength scans. Here, we demonstrate tuning between 1.665 and 1.820 μm at 40 kHz repetition rate with 8 mW average output power. We applied this source to measure the overtone of the C–H stretch in gaseous butane.

Drawbacks, potential improvements of the system and possible applications in other fields are discussed.

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1 Introduction

Wavelength-tunable laser sources are widely applicable to sensing applications such as the measurement of temperature and strain, on-chip biological diagnostics, and the sensing of gas properties (see [1] and references therein). Sensors that can capture broad spectral information in short times are especially useful for monitoring dynamic processes. A cornerstone for such systems can be a wavelength-agile laser source, whose output wavelength can be swept over hundreds of nanometers within a short time. As an example, we have used a wavelength-agile laser to monitor the chemical evolution in an internal-combustion engine [2]. Ordinarily, a measurement time of less than 100 μs is required in such an application.

A related field of interest in our Department is the study of fuel sprays. Typical fuels have absorption features associated with vibration of the C–H bond. One resonance of the C–H stretch occurs near 3.4 μm. We chose to monitor the overtone of that stretch near 1.7 μm. Our choice is, in part, due to reduced absorption strength [3, 4], which enables measurements in dense fuel vapors, and, in part, due to availability of femtosecond laser sources.

The above task was addressed with a novel laser system which scans from 1.665 to 1.820 μm at a repetition rate of 40 kHz. The purpose of this paper is to present the novel laser source which comprised the following components. Light pulses at 1.56 μm were delivered by a femtosecond fiber laser. The high-power pulses were coupled into an optical fiber, where the irradiance of the light is high ($\sim 25\ \mathrm{TW/m^2}$) because of the small cross section of the fiber. The wavelength of the incoming light was red-shifted by a nonlinear process known as the soliton self-shift effect [5]. In our approach we exploited the dependence of the red-shift on the irradiance coupled into the fiber [6]. By rapidly modulating the irradiance we generated scans with the above specifications and we demonstrated the ability to measure absorption spectra of butane vapor.

Besides demonstrating the potential of this light source, we also discuss its limitations in detail and how they might be addressed.

Although our system originally was developed for the diagnostics of fuel sprays in internal-combustion engines, there are a wide range of alternative applications. Examples are particle-sizing by spectral analysis of Mie scattering and the monitoring of liquid-phase or solid-phase spectral features of various substances.

2 Experimental apparatus

The experimental setup is depicted in Fig. 1. A mode-locked erbium fiber laser (IMRA Femtolite) delivers 300-fs long pulses at a repetition rate of 50 MHz. The emission wavelength is centered around 1.56 μm, and the average power is 120 mW. All optical powers stated in this work were measured with a bolometer (Melles Griot 13PEM001). The output of the laser is coupled with a lens into a 50-m long single-mode polarization-maintaining fiber (PM fiber; 3M Tiger FS-TI-5129) featuring a mode-field diameter of 6 μm. Although the coupling efficiency is only ∼ 10%, corresponding to an average power of 12 mW, the spectral power of the light coupled into the fiber is high enough to form a soliton via frequency broadening and pulse compression [7]. The soliton is continuously shifted to the red by a process called soliton self-shifting [5]. In a simplified picture of

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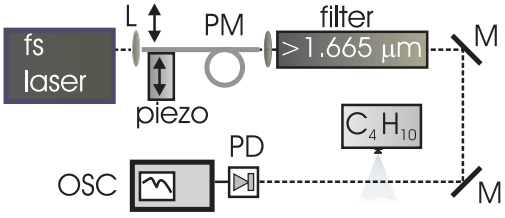

FIGURE 1 Experimental setup. L: lens; PM: polarization-maintaining fiber; M: mirror; PD: photo diode; OSC: oscilloscope. Filter: long-pass filter for wavelengths over 1.665 μm

the process the blue wing of the soliton's spectral profile amplifies the red wing via Raman pumping [8]; the blue wing gets hereby depleted in exchange for increased power in the red wing, and thus the center frequency of the soliton shifts to the red. The soliton continues to red-shift on its own until one of a variety of practical limits are reached. In general, longer fibers, increased input power, and smaller positive fiber dispersions all give increased red-shift.

Raman shifting is an inherently weak process, but due to the high number density of silica and the long interaction length in the fiber, considerable portions of a femtosecond pulse can be red-shifted [9]. The amount of red-shifting realized is sensitive to the input power [8], which is illustrated in Fig. 2 for typical red-shifts attainable with our system. The spectra were recorded with a self-built optical spectrum analyzer with a spectral resolution of $\sim$ 40 nm. The spectral width of solitons for wavelengths below 1.7 μm was determined with a commercial optical spectrum analyzer (Agilent 86142B) to be $\sim$ 15 nm. In Fig. 2a only the pump pulse around 1.56 μm is visible. For increased irradiances (Fig. 2b) one distinguishes unshifted laser light and a red-shifted peak – the soliton – centered around 1.62 μm. In Fig. 2c the irradiance coupled into the fiber is higher and the self-shifted soliton gets not only stronger, but also shifted to almost 1.7 μm. In Fig. 2d the pulse energy coupled into the PM fiber is even higher and the strong soliton is shifted to almost 1.8 μm. Also distinguishable in the Figure is an intermediate peak around 1.63 μm. For an increase in optical power the pulse decays into several solitons at several wavelengths [8], which is why there a a soliton between the fundamental wavelength and the most red-shifted soliton.

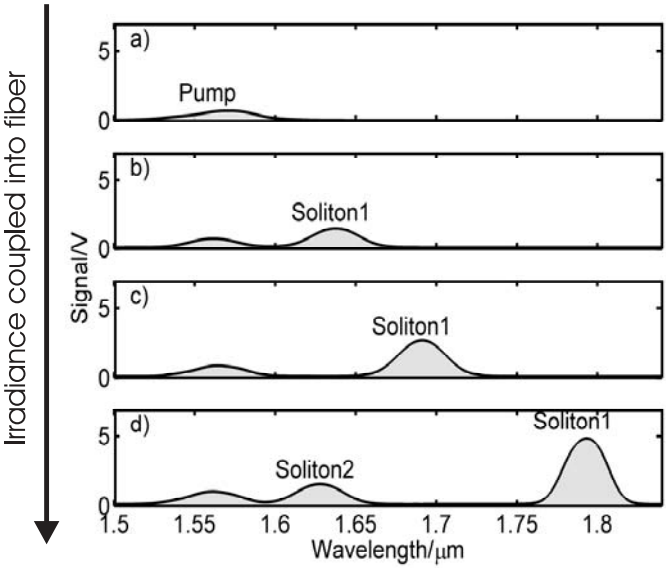

FIGURE 2 Dependence of the soliton-self shift on irradiance in the PM fiber. The irradiance increases from the top to the bottom diagram. In all diagrams residual laser radiation at 1.56 μm (Pump) is present. The red shift of the solitons (wavelength > 1.56 μm) is increasing with irradiance. For elevated irradiances a lower-order soliton emerges (Diagram (d), Soliton 2, $\sim$ 1.630 μm)

The higher the irradiance of the pulses coupled into the fiber the larger the number of red-shifted solitons [8]. Although not all of the input light is transformed into a single, red-shifted soliton, the illustrated intensity dependence can readily be exploited to facilitate compact laser sources that can be tuned over large spectral ranges [6].

Our goal is to scan the wavelength of the first soliton in Fig. 2 over the range from 1.665 to 1.820 μm at a repetition rate of several 100 kHz. The intensity of input light around 1.56 μm can easily be modulated with fiber-coupled lithium niobate optical modulators [10], but these devices are generally limited to only tens of mW average input power and are rather lossy (typically >3 dB) . Other options would be free-space acousto-optical and electro-optical modulators (AOM, EOM). However, in our setup it was not straight forward to incorporate free-space optics. Therefore, we chose an alternative approach that facilitates modulations with a repetition rate over 40 kHz and with a potential upper limit of $\sim$ 1 MHz. The principle of our approach is depicted in Fig. 1. The laser light is coupled into the PM fiber by means of a positive lens. The fiber is attached to a piezo crystal (Thorlabs AE0505D18), whose length can be altered by applying a voltage. The latter is supplied by a function generator (Agilent 33250A). Upon a change in length of the piezo crystal the fiber is moved in and out of focus of the coupling lens and the irradiance of the light coupled into the fiber gets consequently modulated.

For our application we seek to scan from $\sim$ 1.665 to $\sim$ 1.820 μm, and we introduce a long-pass optical filter in the beam path that discriminates the residual input laser pulse and all solitons of shorter wavelength. The long-pass filter is based on a diffraction grating and a spherical mirror. It is described in detail elsewhere [1], and its estimated transmission is 25%.

As shown in Fig. 1 the output from the long-pass filter is directed through a butane spray generated with a simple, inverted commercial butane cylinder. The transmitted light is detected with an extended InGaAs photo diode (New Focus 2034, 700 kHz bandwidth) and the photocurrent is recorded with an oscilloscope (10 MSample/s).

3 Results and discussion

In Fig. 3, two time traces recorded from the output from our system are displayed. One represents the output of the PM fiber when the piezo crystal is run with a sinusoidal voltage at 20 kHz and 2 V_{pp}. The data shown cover an entire period of the crystal's vibration. While at rest the fiber alignment is not optimized. Instead, it is aligned so that at one extreme of the piezo motion the coupling efficiency is maximum and at the other extreme it is minimum. The average power of the soliton was 2 mW, which was sufficient to saturate our detector. The measured power implies 8 mW average power before the spectral long-pass filter, i.e., of the 12 mW average optical power emerging from the fiber (see Sect. 2) only 8 mW lie in a wavelength region over the filter cut-off wavelength of 1.665 μm. As clearly seen in Fig. 3 the self-shifted pulse – I_0 – two sweeps from 1.665 to 1.820 μm during a cycle of 50 μs duration, which corresponds to an average scanning speed of 6 nm/μs. The second trace – I – is a result from directing the beam through a butane spray after all droplets have evaporated. When comparing to the former trace broad dips can be identified. They stem from absorption in the gaseous butane. The wavelength axis shown in the Figure was inferred from a comparison of the absorption features in butane with spectra published in the literature [3].

Obviously the optical power of the source changes during a wavelength sweep. On the first glance this might appear to be a major drawback of our approach, but, on the other hand, this behavior is typical for tunable laser sources, e.g. diode lasers [2]. The observed wavelength dependence is inconvenient, but referencing I to I_0 is an established method to deal with this inconvenience.

The traces in Fig. 3 can be used to derive an absorbance spectrum of butane in the experiment. For this we applied Beer's law, and assumed that the line width of the soliton ($\sim 50\,\mathrm{cm}^{-1}$) is much smaller than the spectral features of the butane absorption spectrum. Because of this rather coarse assumption the spectrum shown in Fig. 4 shows peak absorbances that are systematically lower than the true value.

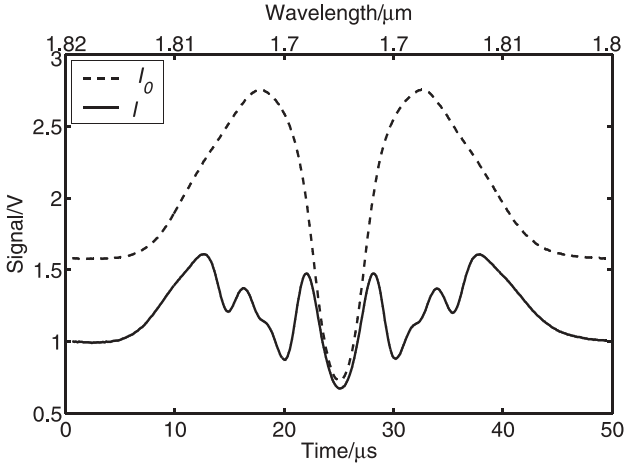

FIGURE 3 Output from the PM fiber as a function of time. One period of the piezo vibration is shown. I_0: Output in the absence of absorption. Due to the induced variation of the coupling efficiency of the laser into the PM fiber (see Fig. 1) both the power and the wavelength of the output vary in time. I: Same as above, but the light is directed through the butane spray depicted in Fig. 1 after total vaporization of the droplets. Spectrally dependent attenuation is clearly manifested in this spectral scan

Also the spectral features of butane are smoothened out, which becomes eminent when comparing our absorbance spectra with results attained with a six times higher spectral resolution (same figure). However, the spectrum recorded clearly demonstrates the viability of our system for the detection and identification of an alkane in the gas phase with a time resolution of 25 μs. The recorded spectrum exhibits an excellent signal-to-noise ratio, and with the current setup we recorded high-quality signals even in a dense butane spray when only ballistic photons were collected. The latter was achieved by coupling the light in a small-core fiber (Corning SMF-28) and thus spatially filtering the transmitted light.

A drawback of our wavelength scanning approach is that the spectral width of the Raman-shifted pulses depends on the input power and hence on the total wavelength shift. This property is different from conventional laser sources and hampers the inference of absorption spectra from recorded traces like those in Fig. 3. However, the spectral width is a slowly varying function of the input power and hence the red shift [9]. Also, the spectral line shape is known [9]. It would therefore be feasible to reliably measure the spectral profile as function of I_0, e.g., by recording the spectral width for several values of I_0 and to interpolate the measured values. By using the known spectral profiles one could then calculate the spectral line shape for

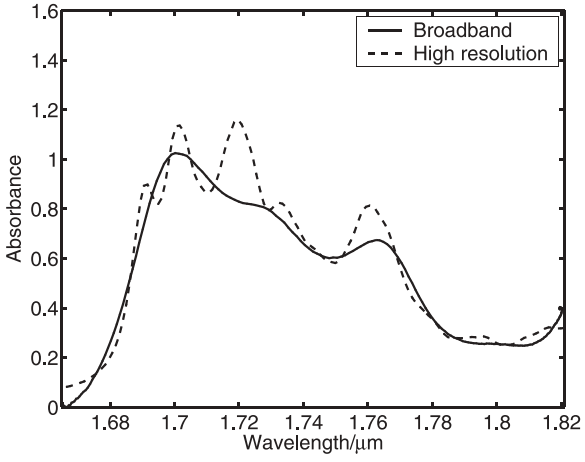

FIGURE 4 Absorbance spectra of gaseous butane at atmospheric pressure. *Broadband*: Spectrum derived from applying Beer's law to the signal traces shown in Fig. 3. Spectral resolution $\sim 50\,\mathrm{cm}^{-1}$. *High resolution*: Spectrum of liquid butane recorded with a spectral resolution of $8\,\mathrm{cm}^{-1}$ [3, 11]

all values of I_0. These profiles could then be used to infer the unperturbed spectrum of the absorber.

Another issue is related to pulse-to-pulse fluctuations of the optical power. Due to an intrinsic variation of the output power of the laser, the power coupled into the fiber and hence also the wavelength of the red-shifted soliton varies. Nishizawa et al. carried out a detailed characterization of a similar laser system [9]. They found the wavelength shift to be almost linearly dependent on the average optical power above a threshold of 3 mW. Extrapolating their calibration curves to our experiment, we infer the average power coupled into the fiber to be between ~ 7 and ~ 15 mW (1.665 and 1.820 nm, respectively). The output power of the our laser was found to fluctuate less than 1% from pulse to pulse. With the figures taken from above this entails a wavelength fluctuation of less than 2 ‰ of the wavelength, which is small compared to the spectral width of the pulses ($\sim 1.4\%$, [9]). With the current system the pulse-to-pulse fluctuation has thus only a small impact on the repeatability of the scans. Another issue is the repeatability of the piezo's movement. We recorded several hundred traces of I_0, and the optical power was found to vary less than 0.3%. The effect of the piezo movement on the wavelength fluctuation is hence even less than that of the aforementioned pulse-to-pulse fluctuation.

The present scanning speed is merely limited by the function generator we use to drive the piezo crystal. With a maximum voltage amplitude of 2 V_{pp} the length of the piezo crystal changes by ~ 30 nm. The resulting displacement of the fiber is too little to induce a sufficient modulation of the coupling efficiency. The observed high modulation at 20 kHz has been identified as a resonance of the fiber end which is slightly cantilevered off the piezo crystal. A custom-designed function generator with a higher peak-to-peak voltage is under construction. With this approach we have so far extended the piezo-based approach to 90 kHz, enabling spectra to be acquired at 180 kHz because of the bi-directional wavelength scanning. A limit for a practical repetition frequency lies around 2 MHz. The spectral width of the red-shifted pulses is about 20 nm in average, and the scan width is ~ 160 nm. Therefore one needs at least eight pulses per scan in order to accurately sample the whole scanning range. Because of the non-linear time dependence of the wavelength on the time (see Fig. 3), we suggest to record at least three times as many samples during one scan. With a repetition rate of the femtosecond laser of 50 MHz this equals to a maximum scan repetition frequency of 2 MHz.

4 Conclusions and outlook

We presented a novel approach to high-speed scanning absorption spectroscopy in broadband absorbers. The system presented is based on the principle of soliton self-shift of femtosecond pulses in polarization-maintaining optical fibers. The source is tunable from 1.665 to 1.820 μm with an average output power of ~ 8 mW and a spectral bandwidth of $\sim 50\,\mathrm{cm}^{-1}$.

The applicability of the system was demonstrated by conducting rapid scans over the C–H overtone in butane at atmospheric pressure. Scans from 1.665 to 1.820 μm were acquired at a repetition rate of 40 kHz, corresponding to an average scan speed of 6 nm/μs. The scans featured and excellent signal-to-noise ratio due to the high spectral power of the light source. The optical power of the source was also found to be high enough to conduct measurements in dense sprays.

Other potential applications of the system presented are the measurement of fuel number densities in homogenous-compression charge compression-ignition engines or gas turbines and droplet sizing by use of spectral analysis of Mie scattering. The system can also be applied to other broadband absorbers within the above wavelength range.

Currently the scanning rate of our system is under improvement with the goal to acquire scans in alkane sprays at a repetition rate of ~ 1 MHz.

As an alternative to the piezo actuator, we are considering the use of an AOM or EOM to modulate the fiber-coupled power rather than the piezo actuator. These devices will enable arbitrary repetition rates, at least up to the 2 MHz limit described above. Furthermore, they will permit arbitrary intensity modulation waveforms, from which we could linearize the wavelength scans as a function of time. We are currently investigating modifications of our fiber-coupling system to accommodate such a free-space device.

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