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Soliton Self-Frequency Shift: Experimental Demonstrations and Applications

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Abstract

Soliton self-frequency shift (SSFS), a consequence of Raman self-pumping that continuously red-shifts a soliton pulse, has been widely studied recently for applications to fiber-based sources and signal processing. In this paper, the fundamentals of SSFS are reviewed. Various fiber platforms for SSFS (single-mode fiber, microstructured fiber, and higher order mode fiber) are presented and experimental SSFS demonstrations in these fibers are discussed. Observation of Cerenkov radiation in fibers exhibiting SSFS is also presented. A number of interesting applications of SSFS, such as wavelength-agile lasers, analog-to-digital conversion, and slow light, are briefly discussed.

Keywords

Nonlinear optics; optical solitons; soliton self-frequency shift (SSFS); tunable optical sources

I. INTRODUCTION

A SOLITON is a wave packet whose temporal profile does not change with propagation. In the early 1970s, Zakharov and Shabat [1] and Hasegawa and Tappert [2] showed theoretically that these solitonic solutions exist for propagation in dielectric fiber. Soon after, Satsuma and Yajima added to the understanding by presenting higher order soliton solutions [3]. The first experimental observation of a fiber-bound optical soliton was in 1980 [4]. Mollenauer *et al.* observed that pulses from a mode-locked laser coupled into a low-loss single-mode fiber (SMF) exhibited dispersive broadening at low power. Then at higher powers, they observed the fundamental and higher order solitons predicted in [1]–[3].

The soliton is a solution of the nonlinear Schrodinger equation (NLSE), which governs light propagation. In the regime where the equation cannot be approximated by either dispersive or nonlinear propagation alone, the soliton solution exists due to the interplay of group velocity dispersion (GVD) and self-phase modulation (SPM). In a soliton, the linear phase shift caused by GVD is completely canceled by the nonlinear phase shift caused by SPM, resulting in a pulse that propagates unperturbed down the fiber. To get this phase

cancellation, the dispersion must be positive (anomalous). Since its discovery, optical solitons have had widespread impact in optics, in particular to telecommunications and ultrafast science.

Dianov *et al.* reported in 1985 a Raman pumping of the Stokes frequency by a sufficiently powerful (capable of producing $N = 30$ soliton) input into a single-mode quartz optical fiber [5]. In 1986, Mitschke and Mollenauer reported a increasing redshift of the center frequency of a subpicosecond soliton pulse with increasing power in standard single-mode, polarization maintaining (PM) fiber [6]. They named the phenomenon soliton self-frequency shift (SSFS). Due to Raman gain, the blue portion of the soliton spectrum pumps the red portion of the spectrum, causing a continuous redshift in the soliton spectrum. This wavelength shift was observed to increase with both input power and fiber length. The mathematical basis of SSFS is described in [7]. Gordon found that the frequency shift per unit length was proportional to τ^{-4} , τ being the pulsewidth. SSFS is not significant for telecom-scale (at least tens or hundreds of picoseconds long) pulses. The long pulsewidth leads to only a fraction of gigahertz shift over tens of thousands of kilometers. The delay between the discovery of the optical soliton and the observation of SSFS was primarily because of the lack of a reliable subpicosecond high-power soliton source.

Other early work in SSFS [8]–[11] showed that for a short pulse at high power (capable of producing $N \approx 10$ order soliton), instead of forming a higher order soliton as expected from [3] and [4], fissioned to form numerous fundamental solitons. These fundamental solitons would then individually shift in frequency. Beaud *et al.* [8] observed the formation of multiple Stokes pulses each with the temporal profile of a fundamental soliton. These Stokes pulses underwent frequency shift, resulting in an output spectrum with spectrally separated soliton peaks. The remaining energy not converted to a soliton was dissipated in a dispersive wave at the source wavelength.

Since its discovery in SMF, SSFS has also been observed in other fiber platforms, including tapered microstructured airsilica fiber [12], high-index core photonic crystal fiber (PCF) [13], [14], hollow-core photonic bandgap fiber (PBGF) [15], and solid silica higher order mode (HOM) fiber [16]. The region of anomalous dispersion for silica limits the SSFS in standard step-index silica-based fiber to wavelengths longer than $1.3 \mu\text{m}$. Microstructured optical fibers and other new fiber designs, on the other hand, have nonconventional mode propagation characteristics [17], [18], which give rise to fiber dispersion profiles previously unattainable by step-index silica-based fibers. These novel fiber structures have extended the accessible region down to the near IR, and even visible wavelengths [18], [19].

Since the frequency shift from SSFS is deterministic, the SSFS has seen much application over the last decade in fabricating fiber-delivered, widely frequency-tunable, femtosecond pulse sources [20], [21]. Other applications of SSFS include analog-to-digital conversion [22], [23] and telecom applications such as signal processing [24], [25], tunable time delays [26], [27], switching and demultiplexing [28]–[30].

In this review, we will describe SSFS as observed in various fiber platforms, namely SMF, high-index core PCF, hollow-core PBGF, and solid all-silica HOM fiber. In addition, we will review applications of SSFS for making tunable and multiwavelength sources, analog-to-digital conversion, and slow light.

II. THEORY

We now briefly outline the mathematical description of SSFS [31], [32]. Light propagation in fiber is governed by the NLSE, which takes the form

$$-i\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u. \quad (1)$$

The right-hand side of (1) shows the GVD and SPM effects on propagation. This particular form of the NLSE does not include loss, higher order dispersion, or other nonlinear terms. It has a solution of the form $u = \text{sech}(t)\exp(iz/2)$. This solution has a length invariant temporal profile and is called the fundamental soliton. The variables for time t , propagation distance z , and electric field u are in soliton units. These parameters are normalized to characteristic pulsewidth, length, and power ($|u|^2 = P$) defined as, respectively,

$$t_c = \frac{\tau}{1.763}, \quad z_c = \frac{1}{|\beta_2|} t_c^2, \quad P_c = \frac{\lambda A_{\text{eff}}}{2\pi n_2} \frac{1}{z_c} \quad (2)$$

where τ is pulsewidth at full-width half-maximum (FWHM), β_2 is the GVD parameter, λ is center wavelength, A_{eff} is effective mode area, and n_2 is the nonlinear refractive index (Kerr coefficient). Higher order solitons, characterized by soliton order N , also exist.

When pulses are short (on the order of picoseconds or less), higher order dispersive and nonlinear terms must be considered. If we rearrange the NLSE such that all the higher order terms appear on the right-hand side, the equation becomes:

$$i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u = i\delta_3 \frac{\partial^3 u}{\partial t^3} - is \frac{\partial}{\partial t} (|u|^2 u) + \tau_R u \frac{\partial |u|^2}{\partial t}. \quad (3)$$

The three terms on the right-hand side of (3) are for third-order dispersion, self-steepening, and intrapulse Raman scattering, respectively. δ_3 , s , and τ_R are the relevant coefficients for these effects:

$$\delta_3 = \frac{\beta_3}{6|\beta_2|\tau}, \quad s = \frac{2\pi c}{\lambda\tau}, \quad \tau_R = \frac{T_R}{\tau}. \quad (4)$$

The constant T_R , the Raman response, is a reasonable approximation for the full integral form when pulses are longer than a few optical cycles.

By treating the Raman effect as a perturbation on the standard NLSE (1), Gordon analytically derived a dependence of the frequency shift (in terahertz per kilometer) on pulsewidth [7],

$$\frac{dv}{dz} \propto \frac{h(\tau)}{\tau^4} \quad (5)$$

where $h(\tau)$ is a function integrated from the Raman gain spectrum [32], but is approximately equal to 1 for pulses on the order of 100 fs. More generally, the higher order NLSE (3) can be solved numerically by a split-step Fourier method [31]. In general, numerical solutions to the higher order NLSE predict the SSFS behavior with good accuracy.

III. FIBER STRUCTURES

SSFS has been observed in many types of fibers. In early experiments in SMF, SSFS has been observed between 1.3 and 2 μm . Microstructured optical fibers such as PCF and PBGF have been shown to exhibit SSFS between 0.8 and 1.7 μm . Recently, SSFS has also been shown in HOM fibers between 1 and 1.3 μm . The behavior of SSFS in these fiber platforms

is dictated by the dispersion and nonlinearity of the fibers. Table I summarizes past representative experiments of the SSFS.

A. SSFS in SMF

Total dispersion of a fiber is the sum of material dispersion D_m and waveguide dispersion D_w . Since the waveguide dispersion of the fundamental mode in standard SMF is normal ($D_w < 0$), soliton propagation is largely limited by the region of anomalous material dispersion in silica $\lambda > 1.3 \mu\text{m}$.

The fundamental (LP_{01}) mode propagating in a standard step-index SMF has normal waveguide dispersion ($D_w < 0$). We can understand this by considering the mode evolution of the LP_{01} mode. As wavelength increases, the LP_{01} mode monotonically transitions from the high-index central core to the surrounding lower index regions, yielding an effective index that decreases with wavelength. Since the velocity of light is inversely related to the index, the LP_{01} mode experiences smaller group delays as wavelength increases. D_w , which is the derivative of group delay with respect to wavelength, is thus negative (normal) for the LP_{01} mode.

The first discovery of SSFS was made in PM single-mode step-index fiber [5], [6]. Mitschke and Mollenauer [6] observed up to 10 THz shift of an input at $1.5 \mu\text{m}$, about 75 nm shift. Since then, there have been numerous demonstrations of SSFS in standard PM SMF showing shift over different wavelengths. Beaud *et al.* [8] showed wavelength shift from 1.36 to $1.54 \mu\text{m}$, Nishizawa *et al.* showed a redshift up to $2.03 \mu\text{m}$ [33]. Many other groups have shown SSFS in PM SMF in between these wavelength ranges [20], [34]–[36]. Other efforts include demonstrations in doped fiber amplifiers [37], highly nonlinear fiber [38], birefringent fiber [39], [40], fiber with length-variable dispersion [41], as well as non-PM fibers [34], [42], [43].

In addition to demonstrations of SSFS, suppression of SSFS has also been observed in SMF by bandwidth-limited amplification [44] and propagation near a zero dispersion point [45], [46]. The propagation of solitons near the zero dispersion wavelength is particularly interesting due to the generation of the Cerenkov radiation. With the introduction of perturbations such as higher order dispersion, the stable soliton solution breaks down, allowing the transfer of energy between the soliton in the anomalous dispersion regime and newly shed dispersive radiation in the normal dispersion regime. Such energy transfer occurs most efficiently in fibers for solitons near the zero-dispersion wavelength. The spectral regime to which energy couples most efficiently has been dubbed “Cerenkov radiation” due to an analogous phase matching condition in particle physics. The phenomenon of Cerenkov radiation in fibers is often associated with SSFS as it allows a convenient mechanism for more efficient energy transfer between the soliton and the Cerenkov band. When the third-order dispersion is negative, SSFS will shift the center frequency of the soliton toward the zero-dispersion wavelength, resulting in efficient energy transfer into the Cerenkov radiation in the normal dispersion regime. A more rigorous description and analytical derivation of Cerenkov radiation in fibers can be found in various theoretical works [46]–[48].

B. SSFS in Microstructured Optical Fiber

Newer fiber designs that exhibit different mode propagation characteristics allow for positive waveguide dispersion values. Positive waveguide dispersion larger than the magnitude of negative material dispersion can then achieve anomalous dispersion at previously unattainable wavelengths. In addition, these newer fiber platforms can be engineered to have different dispersion profiles by dimensional scaling or tuning of index

parameters. We can divide the microstructured optical fibers discussed here into two main groups: index-guided PCFs and hollow-core PBGFs. We will use PCF to refer to the index-guided structures and PBGF to refer to the hollow-core structures.

The light guiding mechanism in PCF is index guiding (total internal reflection), as with conventional solid silica SMF. Due to the high index contrast between the silica core and airhole clad, PCF can be thought of as a thin silica strand in air. Such a structure can have large anomalous dispersion over the wavelength regions where silica is normally dispersive [19]. In addition, the photonic crystal lattice that forms the cladding can be designed to give a wide range of dispersion profiles [17]. The small core size, and thus, small effective area of PCF enable observation of nonlinear effects at low pulse energies.

PBGFs, on the other hand, with its low-index core, does not guide with total internal reflection. Instead, it guides light by the bandgap effect created by the periodic lattice that surrounds the central defect [49]. As with PCFs, the dispersion of PBGFs can be engineered by appropriate design of the photonic crystal lattice cladding. The appeal of PBGF lies in its hollow core: low nonlinearities enable high-energy pulse delivery [15].

The first demonstration of SSFS in an index-guided microstructured optical fiber was in a tapered PCF by Liu *et al.*, showing wavelength shift from 1.3 to 1.65 μm [12]. Later, Washburn *et al.* [13] as well as Cormack *et al.* [14] demonstrated SSFS in untapered PCF in regions of normal silica dispersion ($\lambda < 1.3 \mu\text{m}$). Since these early demonstrations, groups have shown wavelength shifts within the wavelength range of 0.6–1.7 μm [14], [50]–[56]. As was shown in SMF, suppression of SSFS in PCF has also been demonstrated by propagation near a zero-dispersion point and generation of Cerenkov radiation [57].

In addition to the demonstrations in index-guided PCFs, Ouzounov *et al.* recently demonstrated the SSFS in a hollowcore PBGF. For propagation in an air-filled PBGF, they observed SSFS of 60 nm from 1.47 to 1.53 μm [15].

The wavelength access provided by dispersion engineering in these microstructured fibers is exciting; however, each novel fiber design has limitations in allowed pulse energies. The pulse energy required to support stable Raman-shifted solitons in index-guided PCFs and hollow-core PBGFs is either very low, a fraction of a nanojoule for silica-core PCFs [13], [54], or very high, greater than 100 nJ (requiring an input from an amplified optical system) for hollow-core PBGFs [58]. The lowenergy limit is due to high nonlinearity in the PCF. In order to generate large positive waveguide dispersion to overcome the negative dispersion of the material, the effective area of the fiber core must be reduced. For positive total dispersion at wavelengths less than 1.3 μm , this corresponds to an A_{eff} of 2–5 mm^2 , approximately an order of magnitude less than the conventional SMF. The high-energy requirement for the PBGF is due to low nonlinearity in the air core where the n_2 of air is roughly 1000 times less than that of silica. These extreme ends of nonlinearity dictate the required pulse energy (P) for soliton propagation, which scales as $P \propto D A_{\text{eff}}/n_2$. In fact, most PCF and tapered fibers with positive dispersion are intentionally designed to demonstrate nonlinear optical effects at the lowest possible pulse energy. On the other hand, hollow-core PBGFs are often used for applications that require linear propagation, such as pulse delivery. For these reasons, previous work showing SSFS below 1.3 μm were performed at soliton energies either too low or too high (by at least an order of magnitude) for many practical applications, where wavelength-tunable bulk solid state lasers are currently the mainstay for the excitation source [59].

C. SSFS in Higher Order Mode Fiber

HOM fiber, in contrast with microstructured optical fibers, with its large A_{eff} and the moderate nonlinearity (both comparable to conventional SMF), shows promise for supporting self-frequency-shifted solitons of pulse energies 1–10 nJ. Such an exciting new fiber type was recently demonstrated that yields strong anomalous dispersion in the 1 μm wavelength range [18]. This all-solid silica fiber structure is index-guided as with SMF. This represents a major breakthrough in fiber design because it was previously considered impossible to obtain anomalous dispersion at wavelength shorter than 1.3 μm in such an all-solid silica fiber. The key to the design was the ability to achieve strong positive (anomalous) D_w for the LP_{02} mode a higher-order mode of a specially designed HOM fiber. Combined with in-fiber gratings, this enabled construction of an anomalous dispersion element with low loss ($\sim 1\%$) and A_{eff} of approximately 44 μm^2 .

In contrast to the normal waveguide dispersion of the LP_{01} mode, the LP_{02} mode actually exhibits anomalous waveguide dispersion. The LP_{02} mode, instead of transitioning to the lower index cladding with increasing wavelength, may be designed to have the opposite mode evolution: as the wavelength increases, the mode transitions from the lower index regions to the higher index core. With increasing wavelength, the effective index increases, and consequently, the group velocity decreases. Thus, the LP_{02} mode experiences larger group delays as wavelength increases. D_w is then positive (anomalous) for the LP_{02} mode.

In fact, very large positive values of D_w can be obtained, vastly exceeding the magnitude of (negative) D_w . This yields a mode with positive total D (anomalous dispersion). Note that this evolution is governed by the various high index regions of the waveguide, which can be modified to achieve a variety of dispersion magnitudes, slopes, and bandwidths. This yields a recipe to obtain positive dispersion in a variety of wavelength ranges. In fact, the enormously successful commercial dispersion compensation fiber was designed to achieve a variety of dispersion values based on the same concept [18], [60].

We recently demonstrated SSFS from 1.06 to 1.2 μm with up to 57% power efficiency in an HOM fiber [16]. The HOM fiber used in our experiments has positive dispersion [~ 60 ps/nm·km] below 1.3 μm and a relatively large effective area [18], approximately ten times that of index-guided PCFs for similar dispersion characteristics. Through soliton shaping and higher order soliton compression within the HOM fiber, we are able to generate clean 49 fs pulses from 200 fs input pulses.

In addition, we also observe redshifted Cerenkov radiation in the normal dispersion regime for appropriately energetic input pulses. The radiation, centered at 1.35 μm , is generated with 20% power conversion efficiency (approximately 25% photon efficiency) [61]. We successfully filter and compress the Cerenkov output pulses to 106 fs. Cerenkov radiation generated in the normal dispersion regime of this HOM fiber can be used to extend frequency shifting even further, or to create a three-color femtosecond source (centered at the pump, frequency shifted soliton, and Cerenkov radiation wavelengths).

Fig. 1(a) shows the dispersion curve for the LP_{02} mode in the HOM fiber used in our experiment. To generate positive dispersion below 1.3 μm while simultaneously maintaining a large effective area, light propagates solely in the LP_{02} mode. A dispersion of 62.8 ps/nm·km at 1.06 μm is comparable to that of microstructured fibers used previously for SSFS [12], [13], [54], and exhibits two zero-dispersion wavelengths at 908 and 1247 nm. The mode profile at the end face of the HOM fiber is shown in Fig. 1(b), demonstrating a clean higher order LP_{02} mode and an effective area of 44 μm^2 .

The HOM fiber module [see Fig. 1(c)] consists of a segment of standard SMF (flexcore), a long period grating (LPG) [62], and 1.0 m of HOM fiber. Light propagates in the fundamental mode in the flexcore pigtail, is coupled to the LP_{02} mode in the LPG (99% mode conversion efficiency), then propagates solely in the higher-order mode through the HOM fiber. We note that the all-silica HOM fiber leverages the standard silica fiber manufacturing platform and retains the low loss properties (for both transmission and bending) of a conventional SMF, allowing easy termination and splicing.

The experimental setup for observing SSFS in HOM fiber is shown in Fig. 1(c). The pump source consisted of a fiber laser (Fianium FP1060-1S) that delivered a free space output of ~ 200 fs pulses at a center wavelength of 1064 nm and an 80 MHz repetition rate. Using a variable attenuator, the input pulse energy was varied from 1.36 to 1.63 nJ to obtain clean spectrally shifted solitons with a maximum wavelength shift of 136 nm (12% of the carrier wavelength), see Fig. 2(a). Theoretical traces from numerical simulation (using the split-step Fourier method) for similar input pulse energy are plotted adjacent to the experimental data in Fig. 2(d). The non-PM nature of the higher order mode fiber does not give rise to any observable instability, as observed from the clean spectra of the solitons as well as the agreement with numerical simulation.

We measure 57% power conversion from the input pulse spectrum to the redshifted soliton for the case of 1.39 nJ input pulses to achieve ~ 0.8 nJ output soliton pulses, see Fig. 2(a). The corresponding second-order interferometric autocorrelation (see Fig. 3) gives an output pulsewidth of 49 fs, assuming a sech^2 pulse shape, showing a factor of four in pulsewidth reduction due to higher order soliton compression (soliton order $N = 2.1$) in the HOM fiber. The measured spectral bandwidth of 35 nm gives a time-bandwidth product of 0.386 that is 23% beyond that expected for a sech^2 pulse shape. We further note the ripplefree, high-resolution spectrum of the shifted soliton at 1.63 nJ input, see Fig. 2(c), indicative of single mode propagation in the LP_{02} mode.

We note the appearance of Cerenkov radiation centered about $1.35 \mu\text{m}$ for 1.45 and 1.63 nJ input pulse energies, see Fig. 2(a). To investigate the Cerenkov radiation, we add a $1.3 \mu\text{m}$ longpass filter to select out the Cerenkov radiation at the collimated output of the HOM fiber module. Also, a pair of silicon prisms is used for dispersion compensation and to simultaneously filter out any residual pump wavelength.

We are able to couple a maximum power of 265 mW (3.31 nJ pulse energy) into the HOM fiber module. At this power level, the residual input, shifted soliton, and Cerenkov radiation can be clearly seen in the output spectrum shown in Fig. 4(a). The optical power residing in the Cerenkov band is ~ 53 mW (0.66 nJ pulse energy), a power conversion efficiency of 20% (25% photon conversion efficiency). We qualitatively match the experimental spectrum in simulation, shown in Fig. 4(b). At this power level, the soliton (centered at approximately $1.2 \mu\text{m}$) has shifted enough energy past the zero-dispersion wavelength so that resonant coupling occurs efficiently at $1.35 \mu\text{m}$ (Cerenkov radiation). Intuitively, growth of the Cerenkov radiation begins exponentially with increasing input power until the “spectral recoil” exerted by the Cerenkov radiation on the soliton cancels the Raman self-frequency shift [63]. After the soliton is frequency locked (at $1.2 \mu\text{m}$ in this experiment), increasing the pump power will only transfer energy to the Cerenkov spectrum instead of shifting the soliton further. Simulation shows that up to approximately 5 nJ can be pumped into the Cerenkov band, after which other nonlinear effects begin to degrade the system. Experimental pulse energies were limited by the pump power that we were able to couple into the HOM fiber module.

Second-order autocorrelation traces of the filtered Cerenkov pulse at the output of the HOM fiber module is shown in Fig. 5(a); it is visibly chirped and has an autocorrelation FWHM of 907 fs. We are able to compress this pulse to 207 fs autocorrelation FWHM, shown in Fig. 5(b), with appropriate dispersion compensation by a silicon prism pair. Dispersion provided by the silicon prism pair (prism separation distance approximately 7 cm in optical pathlength) is $\beta_2 = 0.0065 \text{ ps}^2$ and $\beta_3 = -1.9 \times 10^{-5} \text{ ps}^3$. Applying such dispersion compensation values to our spectrally matched simulation, we obtain numerically an autocorrelation FWHM of 200 fs and a pulsewidth of 103 fs. If we assume the same pulse shape, the experimentally measured deconvolved pulsewidths with and without dispersion compensation are 106 and 465 fs, respectively.

Though not demonstrated in our experiments, light can be easily coupled back into the fundamental mode using another LPG at the output end. Previous work showed that by using a dispersion-matching design, ultralarge bandwidths can be supported by an LPG [62]. Recently, conversion efficiency of 90% over a bandwidth of 200 nm was obtained for a similar fiber structure [64]. Such an LPG will ensure the output pulse is always converted back to a Gaussian profile, within the tuning range. On the other hand, depending on the intended usage, the higher order mode output could also be used directly without mode conversion.

One can imagine that an HOM fiber module could be engineered to produce shifted solitons of different wavelengths and pulse energies with a different dispersion design. For example, simple dimensional scaling of the index profile can be used to shift the dispersion curve of the LP_{02} mode. Our numerical modeling shows that output soliton energy of approximately 2 nJ can be realized if the dispersion curve is shifted $\sim 100 \text{ nm}$ to the longer wavelength side. Additionally, pulse energy can be scaled by increasing D or A_{eff} . Aside from increasing the magnitude of dispersion through manipulation of the index profile and dimensions of the fiber, the effective area can be significantly enhanced by coupling into even HOMs. An effective area of $\sim 2000 \text{ mm}^2$ (more than 40 times this HOM fiber) was recently achieved by coupling to the LP_{07} mode [64].

Indeed, we obtained much improved SSFS performance by dispersion engineering of the HOM fiber. The dispersion is changed by simple dimensional scaling in this case, yielding a dispersion curve with zero-dispersion wavelengths separated by 415 nm. We have demonstrated SSFS below $1.3 \mu\text{m}$ over a 240 nm range [65] (100 nm more than [16]). The shifted spectra from [16] and [65] are shown side by side in Fig. 6. With measured soliton energies above 1.0 nJ, Fig. 6 represents the largest wavelength shift of energetic pulses in the technologically important, but hard-to-access range of $1\text{--}1.3 \mu\text{m}$. The large range of wavelength tunability combined with high pulse energies make this the first practical all-fiber tunable source with performance approaching that of an optical parametric oscillator (OPO) pumped by a modelocked Ti:Sapphire laser.

IV. APPLICATIONS

SSFS has recently been utilized for several interesting applications, among which are laser wavelength tuning, photonic analog-to-digital conversion, and slow light. In this section, we briefly describe these applications.

A. Laser Wavelength Tuning

Using its power-dependent wavelength tuning property, SSFS can be straightforwardly used to provide a widely tunable laser source at different wavelength ranges from a fixed-wavelength input. Nishizawa and Goto demonstrated a compact tunable source over $1.56\text{--}1.78 \mu\text{m}$ by simply varying the input power into the shifting fiber [20]. Other tunable

sources employing SSFS have been shown for 0.8–1.0 μm [53], 1.0–1.3 μm [54], 1.32–1.75 μm [36], and even up to 2 μm [33]. In addition to wavelength tuning by varying input power, it has also been shown that wavelength tuning can be achieved by changing the input polarization to a highly birefringent fiber [40]. Birefringent fibers have been shown to have wavelength tunability achieved by changing input polarization [40]. The birefringence also introduces an additional degree of freedom, which can be used in making multiwavelength sources [39], [66].

Recent demonstrations in HOM fiber [16], [65] indicated wavelength tuning range and pulse energy that could be invaluable for developing an all-fiber, energetic, wavelength-tunable source for a variety of practical applications. For example, the tunable wavelength range of 1–1.3 μm and pulse energy of a few nanojoules are of great interest for *in vivo* multiphoton imaging. SSFS in fiber, along with a fixed-wavelength fiber laser, could be easily integrated into a fiber endoscopy system with turnkey operation.

Not only can SSFS be used to tune laser wavelength, but is also capable of tuning the wavelength at very high speed. Such a wavelength-agile laser is widely applicable to sensing applications such as the measurement of temperature and strain, on-chip biological diagnostics, and the sensing of gas properties (see [67] and references therein). As an example, a wavelength-agile laser based on SSFS was reported by Walewski *et al.* [68]. By rapidly varying the coupling efficiency of an input laser beam into a fiber, a wavelength-agile source sweeping at 40 kHz between 1.665 and 1.820 μm with 0.2 nJ pulse energy was demonstrated. This source was then used to measure the overtone of the C—H stretch in gaseous butane, as shown in Fig. 7. The wavelength sweeping speed is expected to be further increased by using an acoustooptical or electrooptical modulator.

SSFS is a nonlinear process that often contributes to supercontinuum generation [33], [69], [70]. One interesting application of supercontinuum generation is to provide a broadband light source for high-capacity dense wavelength-division multiplexing (DWDM) optical transmission. In some cases, it is desirable to suppress SSFS in order to maintain spectrum center frequency and to achieve high signal coherence. Takara *et al.* [71] reported a field demonstration of 1046 channel DWDM transmission with a supercontinuum multicarrier source spanning 1.54 mm to 1.6 mm, which was mainly generated through SPM-induced spectral broadening. The channel spacing was 6.25 GHz and the signal data rate per channel was 2.67 Gb/s. All the DWDM channels were successfully transmitted over a 126 km field-installed fiber link.

B. Photonic Analog-to-Digital Conversion

The use of photonic components to realize a high-speed analog-to-digital converter (ADC) has attracted interest since the early 1970s, and extensive studies have been conducted on the “photonic ADC” [72]. ADCs are widely viewed as a bottleneck in high-performance communication and radar. Although the speed of signal processing has improved tremendously in the past decade, improvements in ADC speed and resolution have been much slower. The growing gap between processing speed and ADC speed underscores the need for brand new concepts and revolutionary improvements in ADC performance. Photonic ADCs have attracted much attention recently [73]. The main advantage of photonic ADCs over electronic ADCs is the ultrastable optical sampling pulses.

There are several techniques for applying optics in ADCs [74]–[77]. Although the time-division multiplexing concept is straightforward, it typically requires a large number of active switches for demultiplexing of the signal, raising issues of synchronization, and extinction ratio. Wavelength-division multiplexing techniques are attractive because of their completely passive demultiplexing, but they are hampered by the requirement for a complex

source that must generate a periodically repeating multiwavelength pulse train with very precise interpulse spacing at a very high repetition rate.

Konishi *et al.* proposed to use the power-dependent frequency shift property of SSFS to realize photonic ADC [22]. Recently, Nishitani *et al.* have demonstrated a 4-bit photonic ADC by using SSFS in combination of SPM-induced spectral compression [78]. Fig. 8 shows the schematic of the ADC architecture. The center frequency of each pulse in an incoming optical pulse train is first shifted by SSFS to a lower frequency depending on the power of the pulse. The SPM-induced spectral compression [79] is used to improve the resolution of the ADC. To realize an ADC resolution of N bits, a wavelength demultiplexing filter (DMUX) with 2^N-1 output ports is needed to separate the different frequency, and thus, power levels. Following the $1:(2^N-1)$ DMUX, $N(2^{N-1}:1)$ optical couplers are used to group the DMUX outputs into N branches that correspond to the N bits according to the binary conversion table. In this way, the optical complexity scales *exponentially* with the resolution of this type of photonic ADC.

Xu and Liu [23] proposed a method to significantly reduce the optical complexity associated with the SSFS-based photonic ADC. To realize an N -bit ADC resolution, a $1 \times N$ passive splitter and N wavelength interleaving filters are used to output the digital code (see Fig. 9). Therefore, the optical complexity scales *linearly* with the ADC resolution. In addition, adiabatic soliton spectrum compression is used to increase the ADC resolution.

The spectral breathing technique makes possible large SSFS while maintaining a narrow spectral bandwidth, and thus, high sampling rates with high resolution. More importantly, the proposed signal processing method using a set of interleaving filters results in flash ADC with a remarkable linear scaling between the number of comparators and the number of bits resolved, instead of the usual exponential dependence. Finally, the $1 \times N$ splitter and the interleaving filters can potentially be integrated on the same wafer, making our proposed scheme more compact and robust. Because the final optical output is already in a digital binary format, one can use digital linearization techniques and clock recovery without adding any system complexity. Based on numerical simulations, a resolution of greater than 6 bits can be achieved.

C. Slow Light

Optical buffering is considered a key component for future optical IP routers. Slow light is a promising means to realize optical buffering. Several slow light techniques using various nonlinear effects have been proposed. For example, stimulated Brillouin scattering [80], stimulated Raman scattering [81], parametric process [82], and soliton collision [83] have been recently suggested. Hybrid systems based on wavelength conversion and fiber dispersion have been also proposed [84]–[86]. An all-optical tunable delay line (TDL) consisting of intensitydependent delay based on SSFS and supercontinuum generation and filtering was recently proposed [27] and demonstrated [87]. A delay tunability of up to 720 ps for a 0.45 ps pulse, corresponding to a delay-to-pulsewidth ratio of 1600, was achieved.

Fig. 10 shows the schematic diagram of the SSFS-based all-optical TDL [27], which consists of two stages. In the first stage, the input peak power of an optical pulse is controlled with an intensity modulator (IM) before the pulse is launched into an anomalous dispersion flattened fiber (ADFF). The central frequency of the pulse is downshifted by an amount proportional to the input peak power due to SSFS. The combination of the SSFS-induced wavelength shift and the dispersion of the ADFF results in an optical delay that is tunable by varying the input peak power to the ADFF using the IM. In the second stage, the delayed optical pulse is launched into a normal dispersion flattened fiber (NDFF) for

supercontinuum generation, followed by optical bandpass filtering at the original signal wavelength.

Fig. 11 shows the experimentally observed waveforms, autocorrelation traces, and spectra at the output of the TDL for various input peak powers [87]. The delay increases with increase of the input peak power. The experimentally observed maximum delay is 720 ps for an input pulse duration of 0.45 ps, which corresponds to a delay-to-pulsewidth ratio of 1600 [87]. One issue with this slow light approach is that the output signal power varies depending on the delay. One way to remedy this problem is to use a saturating optical amplifier at the output of the TDL to limit the power variation.

V. SUMMARY AND OUTLOOK

We have reviewed the fundamentals of SSFS, various state-of-the-art fiber platforms for SSFS, and recent experimental SSFS demonstrations. Several interesting applications of SSFS, such as wavelength-agile laser generation, analog-to-digital conversion, and slow light, were briefly discussed.

The recent experimental demonstration of SSFS from 1.06 nm to 1.3 μm in an HOM fiber indicated the possibility for significantly increased wavelength shift with dispersion engineering. The record magnitude of wavelength shift at pulse energies greater than 1 nJ make this the first practical demonstration of an all-fiber tunable source that approaches the performance of state-of-the-art bulk OPOs. Even larger wavelength shifts and higher pulse energies are expected by using further improved HOM fiber structures that enable both large dispersion and large fiber effective area. Using SSFS in HOM fiber shows great promise for developing a new approach for an all-fiber, compact, energetic, and wavelength-tunable femtosecond source.

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Fig. 1.

(a) Total dispersion for propagation in the LP_{02} mode. (b) Experimental near-field image of the LP_{02} mode with effective area $A_{\text{eff}} = 44 \mu\text{m}^2$. (c) Experimental setup used to couple light through the HOM fiber module.

Fig. 2.

(a) Soliton self-frequency shifted spectra corresponding to different input pulse energies into the HOM fiber. All traces taken at 4.0 nm resolution bandwidth (RBW). Input pulse energy noted on each trace. Power conversion efficiency is 57% for 1.39 nJ input. (b) High resolution trace of the initial spectrum; 0.1 nm RBW. (c) High resolution trace of the shifted soliton for 1.63 nJ input into the HOM fiber; 0.1 nm RBW. (d) Soliton self-frequency shifted spectra calculated from simulation using a 200 fs input Gaussian pulse and shifted soliton energies comparable to those in (a). Input pulse energy noted on each trace.

Fig. 3. Second-order interferometric autocorrelation trace of HOM output for 1.39 nJ input pulses. Autocorrelation FWHM measured to be 92 fs corresponding to a deconvolved pulsewidth of 49 fs.

Fig. 4. Optical spectrum at output of HOM fiber module. (a) From experiment. (b) From simulation. Insets show source spectra on a 30 nm window.

Fig. 5. Intensity autocorrelation traces of Cerenkov pulse: (a) at the output of the HOM fiber module without dispersion compensation, and (b) dispersion compensated pulse. Insets show interferometric autocorrelation traces.

Fig. 6. Spectrum showing SSFS in HOM fiber overlaid with dispersion curves. (a) Initial demonstration [16]. (b) Dispersion shifted design [65]. Zerodispersion wavelength is marked with a dashed line. Residual input is attenuated by 7 dB in both plots to accentuate the wavelength shifted features.

Fig. 7.

Experimental setup. L: lens; PM: polarization-maintaining fiber; M: mirror; PD: photodiode; OSC: oscilloscope. Filter: long-pass filter for wavelengths over $1.665\ \mu\text{m}$ (courtesy Dr. Sanders).

Fig. 8. Schematic of an SSFS-based photonic ADC architecture (courtesy Dr. Konishi).

Fig. 9. Schematic of an ultrafast, N -bit photonic ADC based on the SSFS and wavelength interleaving filters. EDFA: erbium-doped fiber amplifier.

Fig. 10.
Schematic of an SSFS-based TDL (courtesy Dr. Maruta).

Fig. 11.

(a) Experimentally observed waveforms, (b) autocorrelation traces, and (c) spectra at the output of the SSFS-based TDL (courtesy Dr. Maruta).

TABLE I. EXAMPLES OF SSFS IN FIBER

	Fiber Wavelength Range(μ)	Pulse Energy	Reference
PM SMF	1.36-1.54	0.4nJ	Beaud 1987
	1.56-2.03	0.2nJ	Nishizawa 2001
HNLF	1.56-1.72	15pJ	Chestnut 2003
Doped fiber amplifier	1.55-1.60	~1 nJ	Kim2002
Birefringent fiber	1.56-1.70	~0.1 nJ	Nishizawa 1999
Non-PM SMF	1.55-1.7	0.4 nJ	Wei, 2004
	1.55-1.83	60 pJ	Korolev 2007
Tm-Ho	1.97-2.15	2 nJ	Kivisto 2007
Tapered PCF	1.3-1.65	1 nJ	Liu 2001
	0.81-1.13	0.1 nJ	Kobtsev 2004
PCF	0.85-1.05	60 pJ	Washburn 2001
	0.8-1.26	~0.4 nJ	Cormack 2002
	0.78-1.0	~50 pJ	Nishizawa 2003
	1.03-1.33	0.5 nJ	Lim 2004
	0.82-1.35	~10 pJ	Ishii 2006
	1.05-1.69	~0.2 nJ	Takayanagi 2006
PBGF	1.47-1.53	~600 nJ	Ouzounov 2003
HOM fiber	1.60-1.20	0.8 nJ	van Howe 2007
	1.06-1.30	1 nJ	Lee 2007

PM: Polarization maintaining, SMF: single mode fiber, PCF: Photonic crystal fiber (here refers to index-guiding structures), PBGF: photonic bandgap fiber (here refers to hollow core structures), HOM: higher-order-mode