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*Final report*

## **Optical solitons and its applications**

## 1 Introduction to optical soliton. (temporal soliton)

The optical pulses which propagate in the lossless fiber without dispersion were suggested by Hasegawa and Tappert in 1973.<sup>1</sup> These kind pulses were called by the optical solitons because of their stability. When the optical soliton propagate the pulse light wave envelopes in the silica fiber, the optical soliton is formed by a balance of a nonlinear change of the index of refraction in the silica fiber and the group velocity dispersion.

The existence of an optical soliton in fibers is made by deriving the evolution equation for complex light wave by retaining the lowest order of group dispersion and the nonlinearity, which for a glass fiber originates from the Kerr effect. For a typical glass fiber, the optical pulse is described by the nonlinear Schrodinger equation (NSE).<sup>2</sup>

$$i \frac{\partial q}{\partial Z} + \frac{1}{2} \frac{\partial^2 q}{\partial T^2} + |q|^2 q = 0 \quad \langle 1 \rangle$$

Here  $q$  is the normalized amplitude given by  $q = \sqrt{\frac{\omega_0 n_2 g z_0}{c}} E$ . The stationary solution of NSE is a sech(T) function.

$$q(T, Z) = \eta \operatorname{sech} h[\eta(t - t_0)] \exp\left[i \frac{\eta^2}{2} Z + i\sigma\right] \quad \langle 2 \rangle$$

$\eta$  is the amplitude,  $T_0$  is the time central position,  $\sigma$  is the phase and  $Z$  is the normalized distance.

## 2 Soliton dispersion management and its application in all-optical communication.

### 2.1 Soliton enables all-optical communication.

Optical fiber is a good medium for long distance broadband communication. However, the fiber loss and dispersion results in data loss and distortion and therefore limits the bandwidth and working distance of the fiber. Therefore, repeaters were installed in transmission lines to regenerate the optical pulse. But they are very expensive and also bottleneck of the transmission speed. On the other hand, solitons do not suffer distortion from nonlinearity and dispersion. If fiber loss can also be compensated with Raman gain of the fiber,<sup>3</sup> we will have a repeaterless all-optical transmission system. This was first demonstrated by Mollenauer and Smith in 1988.<sup>4</sup> They succeeded in transmitting data with 2.3 GHz bit rate for over 4800 km, without repeaters, using periodical amplification based on the Raman gain of the fiber.

### 2.2 Problems in soliton communication. (Gordon-Haus effect)

Gordon and Haus predicted that the amplifier noise would induce frequency modulation because the coherent amplification is always accompanied by the

generation of spontaneous emission noise.<sup>5</sup> The velocity modulation induced by the frequency modulation results in jitter in arrival times of the soliton pulses and contributes to bit-error rate. This kind of phenomenon is called Gordon-Haus effect, which limits the transmission of 20-Gb/s data stream to less than 40 km.

### 2.3 Solutions to the Gordon-Haus time jitter. (Dispersion management)

One solution of this intrinsic problem was proposed by Forysiak.<sup>6</sup> A stepwise dispersion-profiled fiber was used to match the exponential decay of the soliton energy, and therefore circumvent the need for overly close amplifiers. As a result, 40 Gb/s data was transmitted successfully for over 400 km. (See Fig. 1 for results)

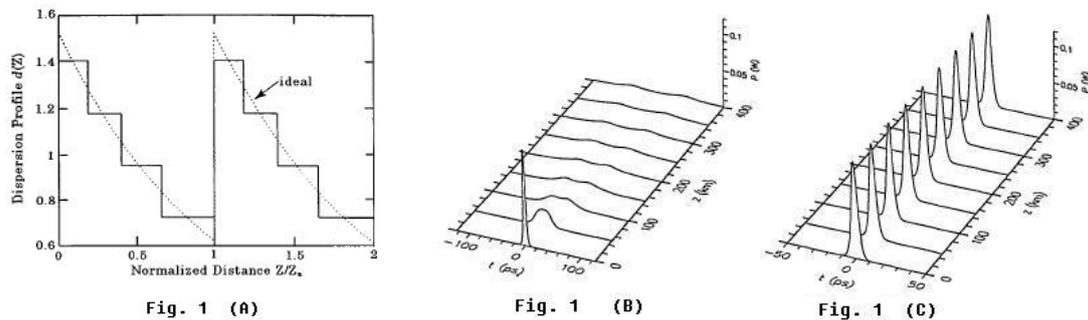


Fig. 1 (A) Exponentially decaying dispersion profile constructed with stepwise constant dispersion.  
 Fig. 1 (B) The unprofiled fiber is unable to support long-distance propagation of the soliton.  
 Fig. 1 (C). The soliton pulse is virtually unperturbed in the fivefold-dispersion-profiled system

Another solution to the Gordon-Haus effect was proposed by Suzuki's group, using the periodic inserted dispersion compensation to suppress the accumulated Gordon-Haus jitter.<sup>7</sup> They achieved successful 20 Gb/s transmissions for 9000 km with inline optical filters which reduce nonsoliton components. (See Fig. 2 for results)

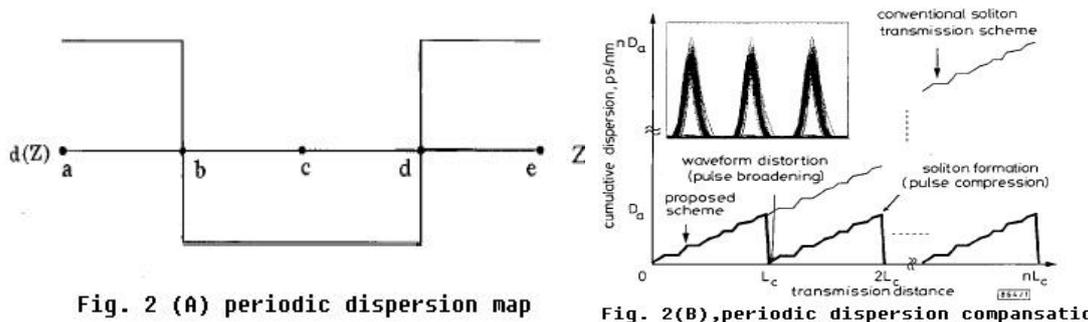


Fig. 2 (A) periodic dispersion map  
 Fig. 2(B), periodic dispersion compensation

### 2.4 Densely dispersion management for ultrahigh bit-rate communication.

While the dispersion management (DM) systems of Forisak and Suzuki have proved to work for conventional fiber communication, they cannot meet the requirement for new high-bit rate (~ 160 Gb/s) applications. A new technique called

Dense Dispersion Management (DDM) was proposed by Liang in 1999.<sup>8</sup> Comparing to conventional DM systems, DDM systems use more closely spaced dispersion compensations and match the energy decaying of the soliton much better. In 2003, Fatome's group demonstrated single-channel 160-GHz transmission for over 896 km using DDM.<sup>9</sup>

### 3 Soliton trapping and its application in all-optical switching

#### 3.1 The idea of soliton trapping.

While solitons propagate in the optical fibers, birefringence can lead to pulse splitting, which is bad for communication applications. Menyuk proposed in 1987 that the Kerr effect, which stabilizes solitons against spreading due to dispersion, also stabilizes them against splitting due to birefringence.<sup>10</sup> In effect, the fractional pulses in each of the two polarizations trap each other and move together as one unit. In the frequency domain, the central frequency of each fractional pulse shifts just enough so that the group velocity of each becomes the same as that of the other. The coupled nonlinear Schrodinger equations describe the soliton trapping behavior,<sup>10,11</sup>

$$-i\left(\frac{\partial u}{\partial z} + \frac{\pi\Delta n\tau}{1.76\lambda^2|D|}\frac{\partial u}{\partial t}\right) = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u + \frac{2}{3}|v|^2 u \quad <3>$$

$$-i\left(\frac{\partial v}{\partial z} - \frac{\pi\Delta n\tau}{1.76\lambda^2|D|}\frac{\partial v}{\partial t}\right) = \frac{1}{2}\frac{\partial^2 v}{\partial t^2} + |v|^2 v + \frac{2}{3}|u|^2 v \quad <4>$$

$u$  and  $v$  are the electric fields along the two principal axes of the fiber;  $t$  is the pulse local time;  $z$  is the normalized distance along the fiber;  $\tau$  is the FWHM of the pulse intensity;  $D$  is the dispersion coefficient;  $\Delta n$  is the index difference between the two principal axes. The terms on the right-hand side correspond to group-velocity dispersion, self-phase modulation, and  $n$ , as derived in the Menyuk paper, the cross-phase modulation creates an attractive potential well along the orthogonal axis and traps the two pulses together.

In our understanding, this process is really not that different from the formation of a single soliton pulse. For a single soliton, the leading half and the trailing half of the pulse modulate each other and create group velocity match between them. For two trapped solitons, the soliton on the slow axis and the soliton on the fast axis modulate each other and also create group velocity match, a trap as called in this case.

#### 3.2 Demonstration of soliton trapping

The first soliton trapping experiment in birefringence fiber was done by Islam in 1989.<sup>11</sup> Its results were shown in Fig. 3. The two-soliton spectra in Fig. 3(b) stay unchanged with different fiber length, despite the birefringence. This confirms that these two solitons are trapped and have the same group velocity.

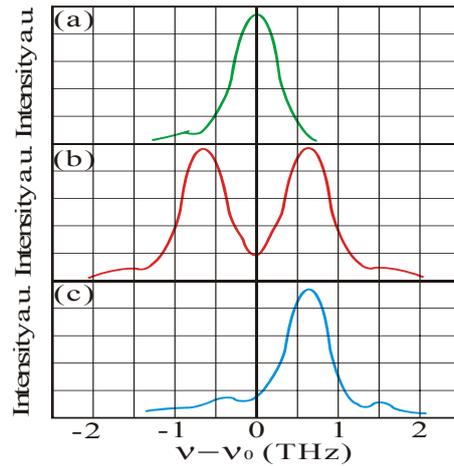


Fig. 3, (a) Single pulse of 42 pJ along the slow axis; (b) Two pulses of 42 pJ along both axes; (c) the same as (b), with a polarizer at the fiber output aligned with the slow axis.

### 3.3 Ultrafast all-optical switch based on soliton trapping.

In 2002, Nishizawa and Goto used a novel way to generate trapped pulse in low birefringence fiber with orthogonally polarized femtosecond soliton pulses.<sup>12</sup> In that experiment, the orthogonally polarized pulse is trapped by the soliton pulse and amplified through its Raman gain.<sup>13,14</sup> The energy of the trapped pulse is finally increased above that of the soliton pulse. The Raman effect, in which the shorter wavelength components of the pulse pumps the longer wavelength components, also increase the wavelength of the pump soliton as it propagates along the fiber. In order to keep the phase matching condition of pulse trapping, the wavelength of the trapped soliton pulse also shifts to the longer wavelength side, keeping the wavelength separation between the two pulses.

Using this phenomenon, Nishizawa and Goto demonstrated an ultrafast all-optical switching in 2005.<sup>15</sup> This optical switch has a maximum repetition rate of 0.83 THz and an extinction ratio of more than 25 dB. The experimental setup is shown in Fig. 4.

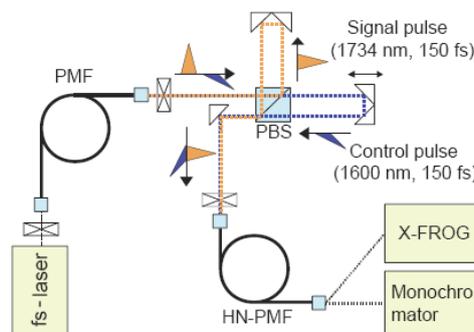


Fig. 4, Experimental setup for pulse trapping in birefringent fiber.

100-fs pulses at the 1.55  $\mu\text{m}$  wavelength were generated and coupled into a polarization maintaining fiber (PMF) with polarization direction inclined from the birefringent axes of the fiber. Thus, the orthogonally polarized two pulses propagate

independently and the wavelength tunable two-colored soliton pulses are generated due to their different Raman scattering effect.<sup>16</sup> The center wavelengths of the control and signal pulses are set respectively as 1600 and 1734 nm. The temporal widths of the generated pulses are 150 fs. The control and signal pulses are divided into two optical axes using a polarization beam splitter.

Fig. 5 shows the results of ultrafast all-optical switching using pulse trapping. The 0.67 THz ultrahigh repetition rate signal pulse train consists of four pulses with temporal separation of 1.5 ps. The respective energies of signal pulses and control pulses were 30 pJ and 60 pJ. The control pulse overlaps with the second signal pulse and trapped it; they copropagate along the fiber. Both pulses shift to the longer wavelength side due to the Raman effect and become slower in group velocity due to anomalous dispersion. As a result, when the control pulse is overlapped with the third and fourth pulses, it does not trap them because there is no group velocity matching. At the end, we can pick off only the trapped signal pulse using a wavelength filter. In this way, an ultrafast ( $\sim 0.64$  THz) all-optical switching has been realized.

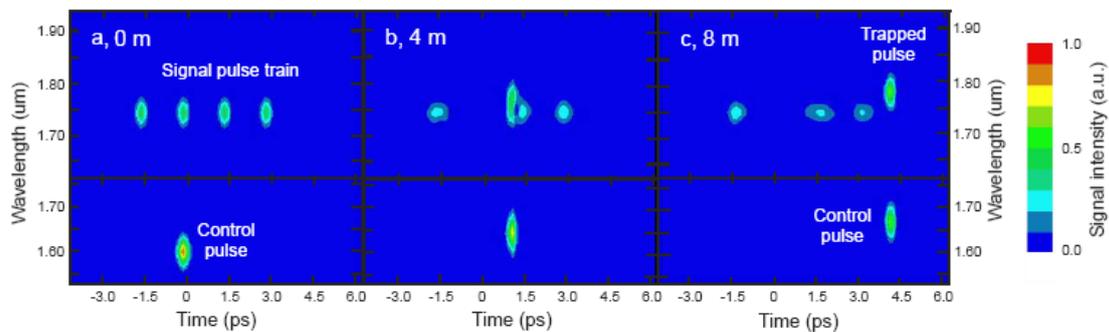


Fig. 5, All-optical switching for a pulse train using pulse trapping. (a) Signal pulse train and control pulse were launched into fiber. (b) The second signal pulse was trapped by the control pulse. (c) Both trapped and control pulses move together. Their wavelengths are increased due to the Raman effect.

## References

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