Soliton Resonances in Dispersion Oscillating Optical Fibers

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Abstract— A novel method to increase the pulse repetition rate by means of fission of second-order solitons in the fiber with periodically modulated dispersion is studied. The experiments confirm the results of numerical simulations. The efficient doubling of the pulse repetition rate takes place in dispersion oscillating fiber (DOF). Good agreement between theory and experiment was obtained.

1. INTRODUCTION

The possibility to generate high quality femtosecond pulses around the 1550 nm wavelength at high repetition rates is important for exploring the potential of ultra-high speed optical time division multiplexed (OTDM) communications. In addition a pulse source with high repetition rate is very essential for optical computing systems, laser spectroscopy and other scientific applications. In this Letter a technique for increasing the repetition rate of a given periodic pulse sequence by splitting of high-order solitons is studied. It is known that the soliton splitting can be stimulated by self-steepening [1, 2], Raman scattering [3, 4] and cubic dispersion [5]. However, it is difficult to control the soliton splitting by these effects. For soliton management, fibers with variable dispersion or nonlinearity were proposed [7–14].

The multisoliton dynamics have their own periodicity [6]. At a distance less than the first half of the soliton period $0.5z_0$, the pulse splits into pulses which have different carrier frequencies. In the second half of the period the process reverses itself. An abrupt change of the dispersion or the nonlinear coefficient interrupts the periodic soliton recovery, and the soliton remains splitted into many daughter solitons. In segmented fiber, the multiple breakups of each soliton generate Cantor set fractals [7]. A step change in dispersion, a localized loss element or filter will generate pairs of pulses with wavelengths that are upshifted and downshifted from the input wavelength [8]. The maximum spectral separation occurs at locations that correspond to $0.5z_0$ for second-order soliton and to $0.225z_0$ for third-order soliton.

There are many contributions to nonlinear pulse propagation in periodic transmission lines with multisegmented fibers. The dispersion-managed soliton [9], split-step soliton [10, 11] and stationary rescaled pulse [12] have been discovered, and they have been analyzed with a focus on the pulse stability. It was shown [13] that periodic perturbation in nonlinear Schrödinger equation induce the generation of dispersive waves and/or the splitting of soliton. Splicing losses and transient processes that arize due to stepwise change of the dispersion restrict the application of multisegmented fibers for soliton splitting.

2. SIMULATION

A longitudinal sine-wave modulation of the fiber core diameter leads to the smooth oscillation of the fiber dispersion [14]. When the period of the modulation of the fiber diameter approaches the soliton period z_0, the soliton splits into pulses propagating with different group velocities. In this work we report experimental realization of the soliton splitting by highly nonlinear dispersion oscillating fiber (DOF).

For analysis of the soliton splitting, the generalized nonlinear Schrödinger equation was solved.

$$\frac{\partial A}{\partial z} + \alpha A(z,t) = -i\frac{\beta_2(z)}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3(z)}{6}\frac{\partial^3 A}{\partial t^3} + i\left(P_{NL} + i\frac{2}{\omega_0}\frac{\partial P_{NL}}{\partial t}\right), \tag{1}$$

where $A(z,t)$ is the complex pulse envelope in a comoving frame, $\alpha = 0.0795\,\mathrm{km}^{-1}$ is the loss coefficient, and ω_0 is the carrier frequency of the pulse. Functions $\beta_2(z)$ and $\beta_3(z)$ take into account dispersion varying along the fiber length. Nonlinear polarization P_{NL} includes effects of Kerr nonlinearity and delayed Raman scattering [6]. The modulation of the fiber core diameter leads to a variation of both the dispersion and the effective nonlinearity. The variation of the effective nonlinearity is much less than the variation of the dispersion [14] and can be neglected.

3. EXPERIMENT

The highly nonlinear DOF with sine-wave diameter modulation was fabricated in the Fiber Optics Research Center. The corresponding variation of the fiber dispersion is approximated by

$$\beta_{2,3}(z) = \bar{\beta}_{2,3}\left(1 + 0.2\sin(2\pi\, z/z_m + \varphi_m)\right), \tag{2}$$

where $\bar{\beta}_2 = -12.76\,\text{ps}^2\text{km}^{-1}$, $\bar{\beta}_3 = 1.4\,\text{ps}^3\text{km}^{-1}$, $z_m = 0.16\,\text{km}$ is the modulation period, φ_m is the modulation phase. Using a 0.8 km length (z) of DOF in these experiments, then $\varphi_m = 0$ at one fiber-end and $\varphi_m = \pi$ at the other fiber-end, according to Eq. (2). Thus, the modulation phase will be different for pulses launched into opposite fiber-ends. Therefore, the nature of the soliton splitting will depend on direction of the light propagation.

Pulse dynamics is calculated in the temporal frame equal to the period $T = 100\,\text{ps}$ of the pulse train used in experiments. The input pulse is

$$A(0,t) = 1.76\frac{N}{T_0}\sqrt{\frac{|\bar{\beta}_2|}{\gamma}}\,\text{sech}\left(1.76\frac{t}{T_0}\right), \tag{3}$$

where N is the soliton order [6], T_0 is the temporal full width half maximum of $|A(0,t)|^2$, $\gamma = 8.2\,(\text{W km})^{-1}$ is nonlinear coefficient.

Figure 1 illustrates the experimental setup. Pritel UOC provides 2-picosecond transform-limited pulses centered at 1550 nm at a 10 GHz repetition rate. The picosecond pulses are amplified by an erbium-doped fiber amplifier. The pulses have typical energies of 2 pJ–20 pJ. Output pulses were characterized using an optical spectrum analyzer (OSA), autocorrelator “Femtochrome” and wide-bandwidth oscilloscope “Agilent Infinium DCA 86100A”. The spectral resolution of OSA was set to 0.002 nm. To detect the doubling of the pulse repetition rate, autocorrelator had a scan range that exceeded the period of input pulse train. To obtain the maximum separation between pulses, the nearly resonant regime $z_m \simeq z_0$ was realized. For initial pulse width $T_0 = 2.1\,\text{ps}$ the soliton period is $z_0 = 0.506\,T_0(\bar{\beta}_2)^{-1} = 0.175\,\text{km}$.

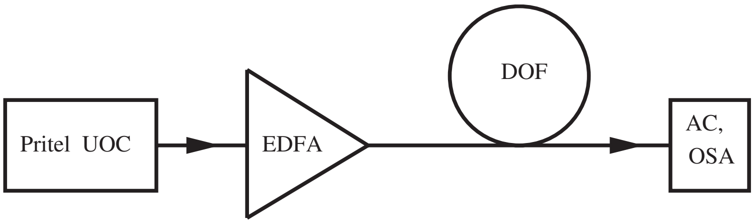

Figure 1: Experimental setup: Pritel UOC, picosecond pulse source; EDFA, Er-doped fiber amplifier; DOF, dispersion oscillating fiber.

At the initial stage the pulse repeat the typical evolution of the breather then splits into separate pulses moving with different velocities (Fig. 2). To initiate the splitting process, two modulation periods of DOF are sufficient (Fig. 2(a)). The normalized intensities of output pulses are 0.36 and 1.0 in Fig. 2(a). Such asymmetry arizes due to the strong effect of the Raman scattering. Without this effect the dispersion oscillation would initiate splitting of second-order soliton into two pulses with equal amplitudes [14]. By means of numerical simulations we have found that effect of the Raman scattering on the splitting of second-order solitons can be controlled by the phase of periodical modulation of the fiber dispersion (2). For $\varphi_m = \pi$ (2) the soliton splits into two pulses with identical amplitudes.

The splitting of the soliton was detected both by the autocorrelation curves (Fig. 2(b)) and by change of the spectrum of the output pulse (Fig. 2(c)). The bandwidth of the oscilloscope is not sufficient to detect the output as separate pulses (Fig. 2(d)). The envelope of the spectrum of initial pulses has sech^2 shape. After the splitting the spectrum envelope become broken down

(Fig. 2(c)). Such structure of output spectrum appears due to interference between two pulses with shifted carrier frequencies. In the frequency domain the first pulse with the peak intensity equal 0.36 (Fig. 2(a)) is blue-shifted $(\omega_0 - \bar{\omega}) = -0.043\,\text{THz}$, while the second is red-shifted $(\omega_0 - \bar{\omega}) = 0.084\,\text{THz}$. Here $\bar{\omega}$ is the mean-weighted frequency of the pulse.

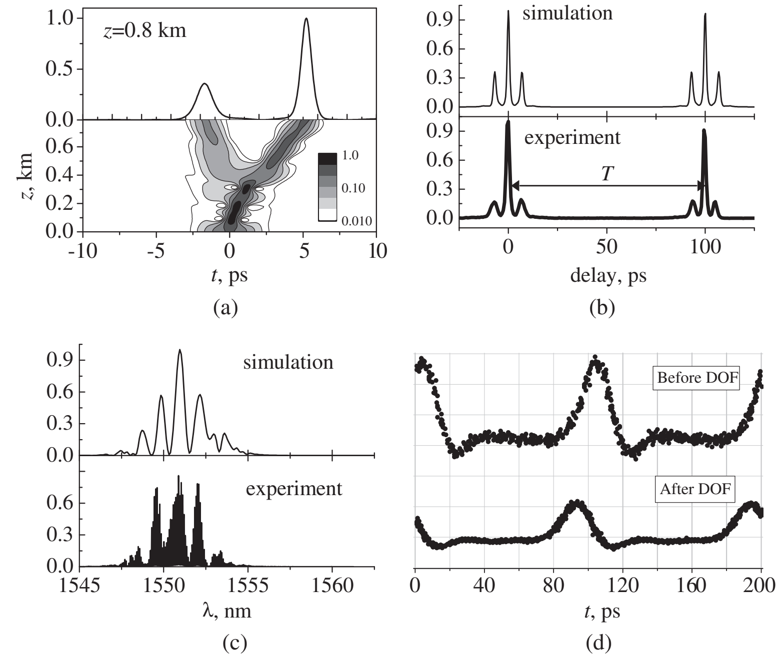

Figure 2: Pulse splitting in dispersion oscillating fiber. (a) Contour plot of pulse trajectory (bottom) and intensity pulse shape at $z = 0.8\,\text{km}$ (top); (b) autocorrelation traces for output pulses; (c) output spectrum; (d) oscilloscope record. $\varphi_m = 0$, $T_0 = 2.1$ ps, input power is 167 mW, for simulation $N = 1.85$ was used.

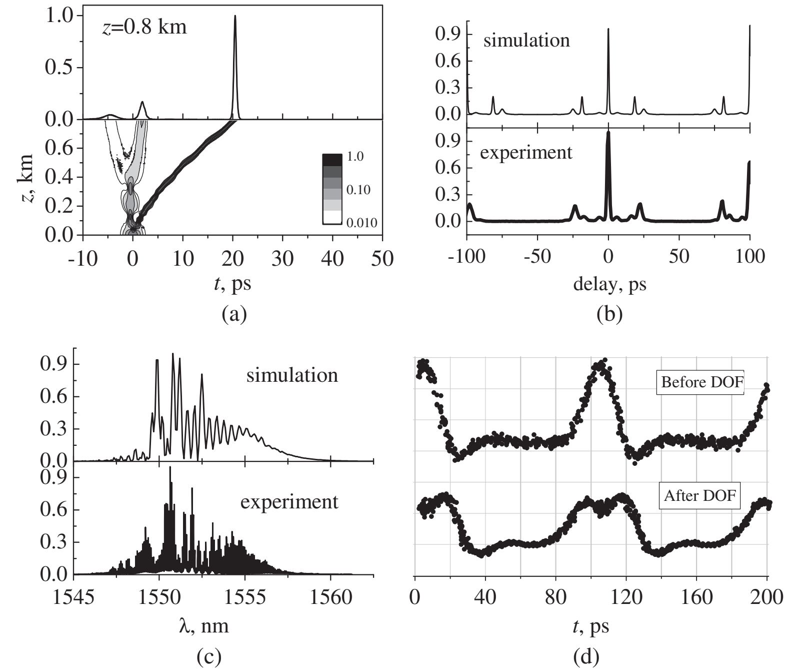

Figure 3: Splitting of soliton under the effect of Raman scattering. (a) Contour plot of pulse trajectory (bottom) and intensity pulse shape at $z = 0.8\,\text{km}$ (top); (b) autocorrelation traces for output pulses; (c) output spectrum; (d) oscilloscope record. Input power is 279 mW, $N = 2.66$. Other parameters are the same as in Fig. 2.

The splitting of the soliton into three pulses is shown in the Fig. 3. Maximum temporal separation between output pulses detected by autocorrelation curve (Fig. 3(b)) and wide-bandwidth oscilloscope (Fig. 3(d)) is 25 ps. Due to the Raman scattering a high-intensity pulse appears after the propagation through only 0.1 km of the fiber (Fig. 3(a)). The central frequency of this pulse is red-shifted $(\omega_0 - \bar{\omega}) = 0.36\,\text{THz}$. Two other pulses that appears after propagation 0.4 km in DOF have frequency shifts $-0.08\,\text{THz}$ and $0.04\,\text{THz}$ correspondingly. As result the output spectrum become broadened (Fig. 3(c)). Fine structure of the spectrum envelope arises due to interference between frequency shifted pulses.

The temporal separation between output pulses increases with the increasing of the peak intensity of input pulse (Figs. 4(a) and (b)). The pulse splitting process begins after one half of the modulation period of DOF (Fig. 4(a)). In this regime the maximum temporal separation equal to the half of the period of initial pulse sequence $T/2 = 50\,\text{ps}$ was achieved.

Due to the stimulated Raman scattering the spectrum mainly broadens into the range of long wavelengths. The spectrum of the pulse with the highest peak intensity (Fig. 4(c), $1555\,\text{nm} < \lambda < 1560\,\text{nm}$) separates from the spectra of other two pulses.

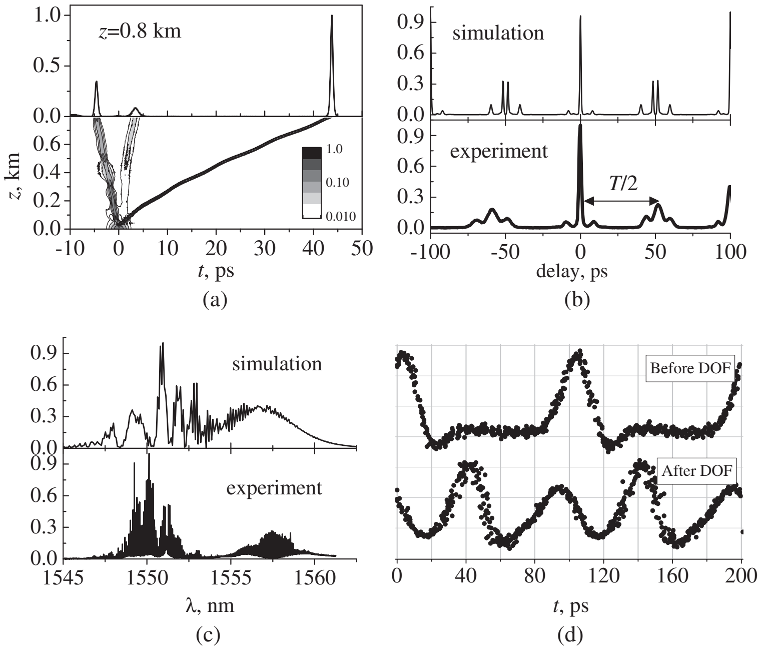

Figure 4: Doubling of the pulse repetition rate. (a) Contour plot of pulse trajectory (bottom) and intensity pulse shape at $z = 0.8\,\text{km}$ (top); (b) autocorrelation traces for output pulses; (c) output spectrum; (d) oscilloscope record. Input power is 325.5 mW, $N = 3.1$. Other parameters are the same as in Fig. 2.

4. CONCLUSION

In conclusion, we have proposed the novel method to multiply the pulse repetition rate of high frequency pulse train in passive fiber. The soliton splitting initiated by DOF was demonstrated. Good qualitative agreement between theory and experiment takes place. Optimization of DOF parameters will allow construction of the all-fiber high-repetition rate source which will produce transform-limited, sech-shaped pulses. Due to the periodical modulation of the fiber dispersion carrier frequencies of resulting pulses are located symmetrically with respect to the initial pulse frequency while the intrapulse Raman scattering contributes to the long-wavelength portion of the spectrum. The initial phase of dispersion modulation function of DOF plays an important role in soliton fission. The splitting process is mainly dependent on the soliton order N which is determined by the pulse peak intensity. Modulation of the pulse peak intensity allows to control both the temporal separation between output pulses and width of output spectrum. The technique described here is simple and efficient.

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