Nonlinear Polarization Rotation for Fiber Lasers with Ultra-High Pulse Energy

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Abstract

This report introduces principles of fiber lasers passively mode-locked by nonlinear polarization rotation (NPR). Dispersion and nonlinearity management of the laser cavity play an essential role in determining the laser operation state. Different soliton operation of the laser is discussed. Taking advantage of weak soltion restriment of per-pulse energy of postive net cavity dispersion cavity, strong energy pulse generation is realizable. In this operation state, largely elongation of cavity making high energy pulse generation with ultra-low repetition rate possible in the laser. Recent progress on high energy pulse laser with the per-pulse energy directly generated up to several μJ is also shown in the report.

Introduction

High energy pulse trains have wide potential applications in regions such as industry, biology and spectroscopy, military and so forth. For generating high-energy optical pulse radiation (μJ~mJ level), usually Q-switching technique are applied to achieve 10-100k Hz pulses operation. Mode-locking technique have been widely used to generated more stable pulses, but usually owing to the cavity length limitation of bulk lasers, the pulse repetition rates are in the MHz-GHz level, leading to relatively lower per-pulse energy. Therefore, to generate high energy pulse train using this approach, extra-cavity amplifiers are usually utilized for outside cavity amplification. Another way to increase per-pulse energy is cavity dumping technique [1], which is achieved by inserting a so-called cavity dumper allowing picking single high-energy pulses out of the cavity at a certain frequency.

This report aims at introducing compact NPR fiber lasers which can directly generate high energy pulses with the per-pulse energy up to μJ level. The principle of NPR mode-locked fiber lasers and different operation states of the laser will be introduced, and dispersion management for high energy pulse generation will be dicussed. In addition, the unique waveguide property of fiber lasers making the elongation of the laser cavity fairly simple, enabling pulse train generation at ultra-low repetition rate and correspondingly high-energy level at the same average power of radiation.

Principle of mode locking by nonlinear polarization rotation

As we known, even a single-mode fiber, actually, supports two orthogonally polarized modes with Even a single-mode fiber, in fact supports two polarized modes with the same spatial distribution. Deviated from the ideal case, in practice all fibers exhibit some modal birefringence (the reflective indexes of x and y axes are different), where $B_m = |n_x - n_y|$ is defined as the degree of the birefringence. If a light is launched with the initial polarization direction oriented at an angle with respect to *x* (or *y*) axis, the birefringence will cause the polarization of the light rotated along the transmission direction of the fiber.

If a high intensity light propagates inside the fiber, the fiber nonlinearity will also play a role on the polarization rotation. This nonlinear polarization rotation can be understood by consider the coupled nonlinear Schrodinger equation:

$$\frac{dA_x}{dz} + \frac{\alpha}{2} A_x = i\gamma\left(|A_x|^2 + 2|A_y|^2\right)A_x,$$
$$\frac{dA_y}{dz} + \frac{\alpha}{2} A_y = i\gamma\left(|A_y|^2 + 2|A_x|^2\right)A_y,$$

where A_x, A_y stand for the slow varying envelop of electrical fields in the slow and fast axes of the fiber respectively; α is the attenuation coefficient; γ is the nonlinear coefficient of the fiber. Solving the equation, we can get the relative phase shift:

$$\Delta\phi_{NL} = \left(\gamma P L_{eff} / 3\right)\cos\left(2\theta\right),$$

where θ is the angle between the slow axis (*x* axis) of the fiber and the light polarization direction, P is the power of the light, and L_{eff} is effective length of the fiber. From the expression we know that for a given distance and input light polarization, the polarization of output depends on the light power.

The mode-locking process can be understood using the ring cavity shown in the Fig.1. The polarizing isolator placed between two polarization controllers acts as the mode-locking element. It plays the double role of an isolator and a polarizer such that light leaving the isolator is linearly polarized. Consider a linearly polarized pulse just after the isolator. The polarization controller placed after the isolator changes the polarization state to elliptical. The polarization state evolves nonlinearly during propagation of the pulse because of SPM- and XPM-induced phase shifts imposed on the orthogonally polarized components. The state of polarization is non-uniform across the pulse because of the intensity dependence of the nonlinear phase shift. The second polarization controller (one before the isolator) is adjusted such that it forces the polarization to be linear in the central part of the pulse. The polarizing isolator lets the central intense part of the pulse pass but blocks (absorbs) the low-intensity pulse wings. The net result is that the pulse is slightly shortened after one round trip inside the ring cavity, an effect identical to that produced by a fast saturable absorber. In other word, the polarization-dependent isolator, working together with the birefringence fiber, can generate an intensity-dependent loss [2, 3], which is identical to that produced by a fast saturable absorber.

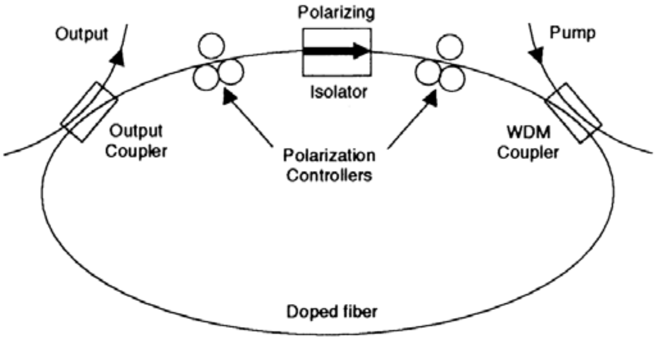

Fig. 1 Schematic design of a fiber laser passively mode locked through nonlinear polarization-rotation.

Ultra-high-energy pulse generation

In mode-locked fiber lasers, dispersion and nonlinearity play an essential role in the laser output. Under different condition of dispersion and nonlinearity, plenty of operation properties of the laser, like normal solition, gain-guided soliton, and noise-like soliton, has been demonstrated [4-7]. Normal soliton is maintained by the balance of a negative dispersion and the fiber nonlinearity, giving a pulse operation of fixed energy. As a result, pump level increase usually can only vary the repetition rate of the laser instead of enlarging the pulse energy [2]. Unlike the traditional normal soliton, gain-guided soliton, usually with the cavity dispersion purely positive or totally positive, is maintained through the balance of gain and nonlinear loss of cavity [7]. In this lasers, soliton effects which tend to shape the pulses to a given shape and energy can be much weaker, and in this case enhancing the pump power will indeed greatly enlarge the per-pulse energy [7]. In the short-cavity regime (several meters), pulse energy of *nJ* level have been achieved compared to the output power level of *pJ* for the other kind of soliton pulse energy in this laser. Moreover, no cutoff energy has been found when the pump is increased or cavity is elongated.

Recently, up to μJ pulse energy has been reported by strongly increasing the cavity length to around 10 km while keeping the laser operating in the gain-guided state [8, 9]. As the pulse repetition rate of a mode-locked laser is inversely proportional to its resonator length, lower pulse repetition rates and, consequently, higher pulse energy at the same average power of radiation was achievable. The scheme of such a typical laser is shown in Fig.2. It is an Yb-doped fiber laser with a cavity length of 8 km. The light is output from the cavity via a fiber polarization splitter. The Yb-doped fiber serves as the active medium of the laser that is pumped via a multi-mode coreless fiber. The length of the active Yb-doped fiber is 10 m, and the core diameter is 7 μm. The active fiber is pumped by a multimode diode laser with an output power of up to 1.5 W at a wavelength of 980 nm. Mode-locking can be readily realized by simply tuning the polarization controllers inside the cavity. Fig.3 shows the typical auto-correction trace of generated pulses. It is a 170 ps pulse train with 37k Hz repetition rate and per-pulse energy of 4 μJ.

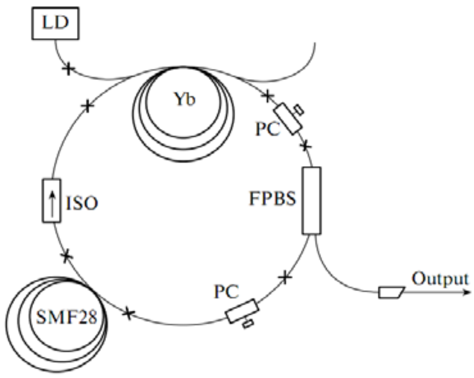

Fig.2. sketch of the fiber laser with ultra-long cavity. PC: polarization controller; ISO: isolator; LD: laser diode.

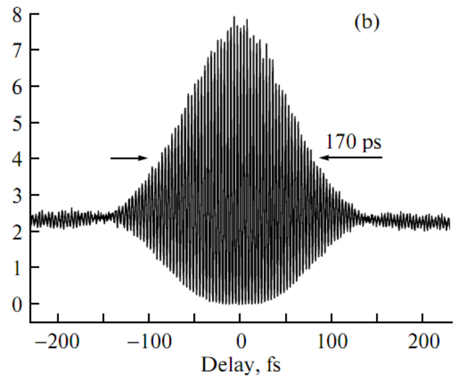

Fig. 3 Typical auto-correlation trace of the output pulses.

Conclusion

Nonlinear polarization rotation technique for generating high-energy mode-locked pulses is stated in this report. Spring from the unique properties of the fiber waveguide, both the cavity length and the dispersion can be readily controled in these lasers. Choosing the gain-guided operation state which can bypass the soliton restriction of per-pulse energy, together with effectively enhance the cavity length, ultra-high energy pulse up to several μJ can be directly generated from the laser. The results also demonstrate the posibility of generating mode-locking of ultra-long cavity.

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