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Photonic Crystal Fiber (PCF)-Based Multi-Wavelength Laser Using Four-Wave Mixing (FWM) Effect

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Abstract:

Nonlinear effects in fiber gratings and photonic-crystal fibers have attracted considerable attention since 1996. As the FWM can be very efficient at the zero-dispersion wavelength, besides the obvious advantage of shorter fiber requirement, the use of PCF would allow the operation of these nonlinear devices in the wavelength regime outside that of possible using conventional fibers. This is because, PCFs unlike dispersion shifted fibers (DSFs), can have a zero dispersion wavelength ranging from 550-1550 nm. In this paper, a PCF based multi- wavelength laser is demonstrated using a FWM effect in a linear cavity resonator. A bi-directionally pumped Bismuth-based erbium-doped fiber (Bi-EDF) is used in the resonator to generate an erbium laser which interacts with a tuneable laser source signal in the PCF to generate a multi-wavelength comb. Thus the area of photonic crystal fibre (PCF) technology has progressed rapidly in recent years and has been successfully applied to the development of a variety of photonics devices and applications.

Keywords: *photonic crystal fiber, Four-wave mixing, Bismuth-based Erbium- doped Fiber, dispersion shifted fibers.*

I. INTRODUCTION

Optical nonlinear effect in fiber optics is one of the interesting topics which has many applications in the development of optical fiber devices. This effect is originated from the nonlinear refractive index (optical Kerr effect) and is responsible for many phenomenon such as self-phase modulation (SPM), cross phase modulation (XPM) and four-wave mixing (FWM) (Agarwal, 2007, Mashade and Aleem, 2009). In the FWM process, light is generated at new frequencies through the conversion of optical power from the original signal wavelengths, or in quantum-mechanical terms FWM occurs when photons from one or more waves are annihilated and new photons are created. These new photons are created when two or more frequencies of light propagate through a nonlinear medium, provided that the condition known as phase matching is satisfied. The phase-matching is a function of pump power, signal spacing and chromatic dispersion (Ahmed et.al., 2009). Two photons of the pump source generate two sidebands (Stokes and anti-Stokes or signal and idler waves (Agarwal, 2007), which must be phase matched along the fiber length for optimum efficiency. However, it is difficult to maintain the phase matching over a long length of fiber. Therefore, many research works have been focused on achieving FWM effect in the highly nonlinear fibers such as dispersion shifted fiber (DCFs) and photonic crystal fibers (PCFs) (Pachnicke et.al.,2006, Belardi et.al., 2002). These fibers have a large nonlinear coefficient and the FWM can be achieved using a very short fiber segment. The FWM effect can be used to achieve multi-wavelength laser operation that is useful for applications in wavelength converters (Inoue and Toba, 1992) optical parametric oscillator (OPO) as well as laser source for the WDM system.

II. MATERIALS AND METHODS

Experimental FWM Setup for the Proposed PCF-Based Multi-Wavelength Laser

The experimental setup for the PCF-based multi-wavelength laser is shown in Figure 1. It consists of a Bi-EDF approximately 2.15 m in length. The Bi-EDF is pumped bi-directionally using two 1480 nm lasers. A 20 m long PCF is used as a non-linear gain medium and a WSC is used to combine the pump and laser wavelengths. The PC is used to control the birefringence of the linear cavity so that the power of the laser generated can be controlled. Two optical circulators designated as OC1 and OC2 in which port 3 is connected to the coupler and then to port 1 is used at both ends of system to act as a reflector. Two couplers, designated as C1 and C2, is incorporated at OC1 and OC2 to tap the output and inject a pump signal respectively as shown in Figure 1. An external cavity TLS with the maximum power of 6 dBm is used as the pump signal. The output of the linear cavity BEFL is tapped from the output coupler C1 and is characterized by an OSA. The output ratio of C1 is fixed at 5% and the coupling ratio of C2 port to inject pump power from TLS is varied from 1 to 50%.

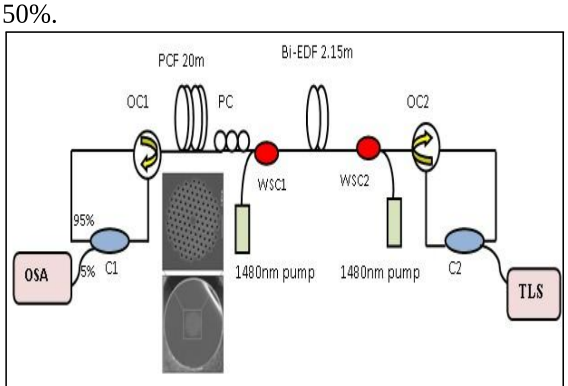

Figure 1: Experimental FWM setup for the proposed PCF-based multi-wavelength laser.

The operating wavelength of the multi-wavelength laser is determined by the bi-directionally pumped Bi-EDF gain spectrum which covers the long wavelength band (L-band) region from 1565 nm to 1620 nm as well as the cavity loss. The Bi-EDFA has a small signal gain of approximately 30 dB at 1585 nm with a total 1480 nm pump power of 270 mW. The free running spectrum of the Bi-EDF laser (without BP) is also investigated in which the oscillating laser is observed in the 1585 nm region. Therefore, the pump signal is injected at this wavelength region into the linear cavity via C2 and OC2. The Erbium laser and the amplified pump signal oscillate in the cavity and interact in the PCF to generate a multi-line spectrum as shown in Figure 1.

III. RESULT AND DISCUSSION

Figure 2 compares the output spectrum of the multi-wavelength laser at different C2 coupler ratio. The pump power for each 1480 nm laser diode and TLS is fixed at 135 mW and 6 dBm, respectively. As shown in Figure 2, more than 10 lines are obtained for all coupling ratios of C2. The multi-wavelength comb is obtained by precisely varying the TLS signal wavelength from 1583.0 nm to 1585.2 nm and controlling the polarisation state of the light inside the linear cavity using a PC. The injected TLS signal is shown in the spectrum as the highest peak. The wavelength spacing between the lines varies from 0.34 nm to 0.39 nm. The multi-wavelength generation is attributed to the FWM effect, which annihilates photons from both waves to create new photons at different frequencies. At 50/50 coupling ratio, the peak power of most of the lines is lowest compared to other coupling ratios. The reduction of power is due to the reduction of reflectivity at OC2, which subsequently increases the cavity loss and reduces the overall output power of the laser. Although output power and optical signal to noise ratio (OSNR~35dB) in 99/1 port is higher than others, the line spacing does not have the same value.

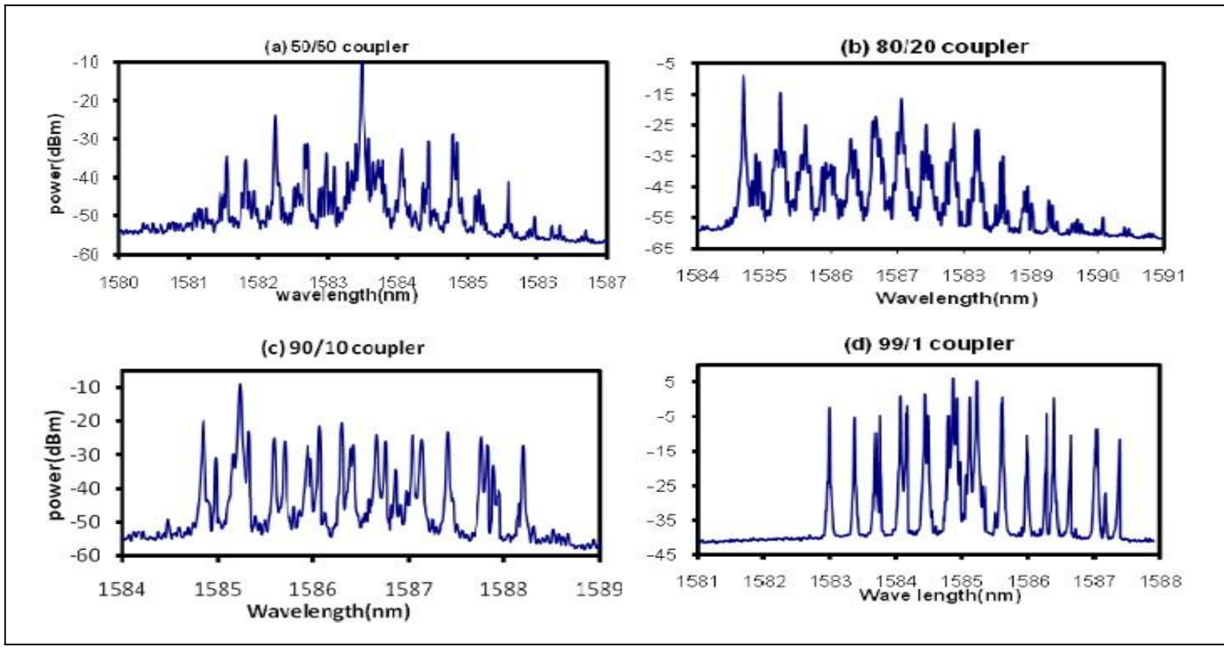

Figure 2: The output spectrum of the multi-wavelength laser at different coupling ratios of C2.

One of the interesting applications of FWM is spectral inversion. Consider a case that involves the input of a strong single-frequency pump wave along with a relatively weak wave having a spectrum of finite width positioned on one side of the pump frequency. FWM leads to the generation of a wave whose spectrum is the "mirror image" of that of the weak wave, in which the mirroring occurs about the pump frequency (Buck, 2001). The representation of this image can be observed in Figure 2(a) where the spectrum is symmetry with the use of 50/50 coupler.

Figure 3 shows the output spectrum of the multi-wavelength laser at different power of each 1480 nm laser diode. The coupling ratio of C2 is fixed at 80/20, in which 20% of the TLS power is injected into the cavity and 80% of the oscillating light is reflected back into the linear cavity. The peak power of each line increases with the 1480 nm pump power increment. At pump power of 69 mW, no multi-wavelength comb is observed as shown in this Figure. This is attributed to the Erbium gain which is very low at this pump power and cannot sufficiently compensate for the loss inside the linear cavity and thus no laser is generated at 1585 nm region. The number of FWM signals increases as the 1480 nm pump powers are further increased as shown in Figure 3. In every FWM peak, a weak Brillouin scattering is also observed with channel spacing of 0.09 nm.

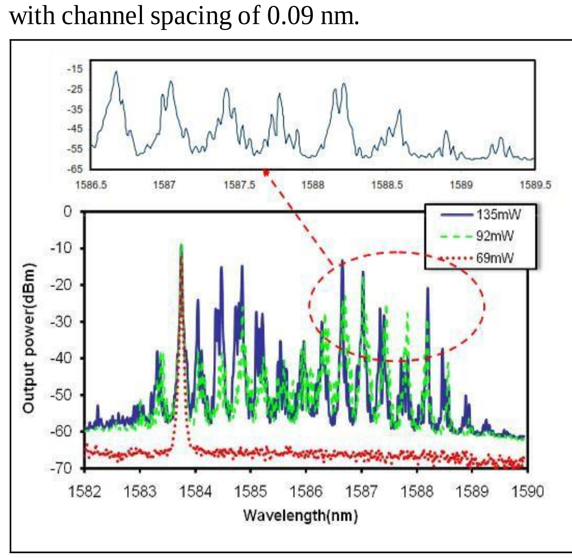

Figure 3: Multi-wavelength spectra 80/20 coupler at different combination 1480 nm pump powers, P1=P2 (mW) at the same time.

In quantum-mechanical terms, FWM can be defined as a phenomena that occurs when photons from one or more waves are annihilated to create new photons at different frequencies. In this process, the net energy and momentum are conserved during the parametric interaction.

IV. CONCLUSION

We have demonstrated a multi-wavelength comb using a FWM process in PCF based on Bi-EDF configuration. The comb generation is due to the interaction between an Erbium laser from a Bi-EDF pumped by 1480 nm laser and a TLS signal. The comb has more than 13 lines with channel spacing varying from 0.34 nm to 0.39 nm. However besides this application, the FWM effect can also be employed for signal amplification, phase conjugation, wavelength conversion and high-speed optical switching.

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