Single-Longitudinal-Mode Continuous-Wave Fiber Optical Parametric Oscillator

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Abstract *Single-longitudinal-mode fiber optical parametric oscillator is realized by resonating independently the signal and idler frequencies in two separate optical cavities, combined with a sub-ring cavity inserted into the signal cavity.*

Introduction

Optical parametric oscillators (OPO) based on $\chi^{(3)}$ nonlinearity of fused silica in optical fiber have long been proposed as a useful means of generating tunable coherent radiation over exceptionally large spectral ranges[1]. To obtain sufficient gain for making a parametric oscillator, usually long length of gain fiber is used[2]. Thus a large cavity length is unavoidable and generates densely-spaced longitudinal modes around the central lasing wavelength. The modes spacing is typically in the order of MHz, so it is difficult to make an intracavity optical filter to select and track a single frequency. Therefore, the typical FOPO is inherentlty multiple-longitudinal-mode[3].

To enable single-longitudinal-mode (SLM) oscillate as demonstrtaed in this paper, we utilize two separate main cavities to resonate the signal and idler frequencies independently. A sub-ring cavity is inserted into the main signal cavity to suppress the longitudinal modes further. If a signal and idler modes overlap perfectly, the energy conservation condition is fulfilled and those pairs of modes which are in exact coincidence are emitted[4]. Hence, if only one exact coincidence lies within the gain bandwidth, the output will become SLM. Based on the above mentioned principle, we present a SLM FOPO in this paper.

Experimental setup and result

The proposed experimental setup is shown in Fig. 1. The gain medium used here is 400-m highly nonlinear dispersion-shifted fiber (HNL-DSF) with the zero dispersion wavelength of 1554 nm. The pump is seeded by an external cavity tunable laser source (TLS) at the wavelength of 1556 nm. To suppress SBS, the light from the TLS is first phase-modulated with 10-Gb/s pseudo-random bit sequence (PRBS) signal via a phase modulator (PM). Polarization controller PC1 aligns the pump's state of polarization (SOP) with the transmission axis of the PM. The SBS can be suppressed by up to 32 dB using this method. Then the pump is amplified by a two-stage configuration of EDFA, in which the first stage (EDFA1) provides small signal gain to prevent self-saturation by amplified spontaneous emission (ASE). Then it is filtered by a 0.35-nm tunable bandpass filter (TBPF1) to reduce ASE noise. After an isolator (ISO1) it is further amplified by the second stage (EDFA2), with a maximum average output power of 33 dBm. Then the pump is coupled into the 400-m HNL-DSF via P-port (transmission band: 1554.89 ~ 1563.89 nm) of a WDM coupler (WDMC1). The high power pump propagates through the HNL-DSF and is then coupled out of the ring cavity through P-port of another similar WDM coupler (WDMC2), while the amplified signal and idler are coupled into the respective ring cavities: firstly through the R-port (reflection bands: 1500 ~ 1551 nm, 1567 ~ 1620 nm) of WDMC2 and subsequently are splitted into two paths by a C/L band WDM coupler (WDMC4). In regard to the signal cavity ①, the signal from the C-port of WDMC4 is filtered by a 0.35 nm bandpass filter (TBPF2) which determines the lasing wavelength and provides the first restriction on the possible oscillating modes. The sub-ring cavity ③ composed of a PC and a 50/50 coupler with a cavity length of 1.6 m is then inserted after TBPF2. After that a 10/90 optical coupler is used to couple out 10% of signal light to provide the output for the FOPO. The isolator (ISO2) ensures unidirectional operation and prevents oscillation by back reflection. PC3 is used to align the signal's SOP with the pump so as to maximize the signal gain. In

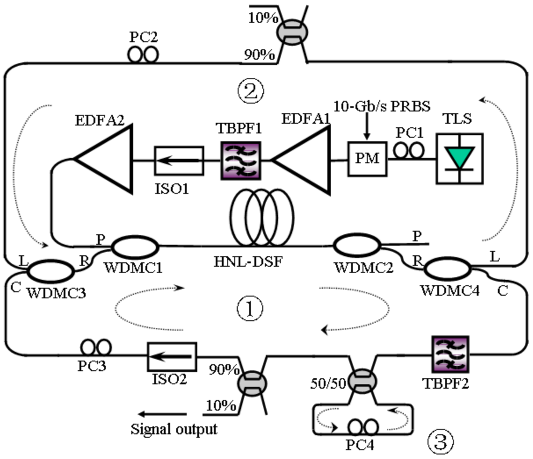

Fig. 1 Schematic diagram of the single-longitudinal-mode fiber OPO: ① signal cavity; ② idler cavity; ③ sub-ring cavity.

regard to the idler cavity ②, the light from L-port of the WDMC4 propagates through a 10/90 coupler for monitoring the idler and a polarization controller (PC2) before entering the HNL-DSF via L port of WDMC3.

The resonant frequencies of ring cavity can be obtained by imposing the condition that the total phase shift along the ring path must equal an integral number of 2π, as can be described as $\beta L = 2m\pi$. Here β is the propagation constant in each ring cavity, L is cavity length and m is positive integer. The PCs in the signal and idler cavities must be tuned to the SOP at which the OPA gain is maximized. The modes spacing, as well as the free spectral range (FSR) is $FSR = c/nL$, where c is the speed of light in vacuum and n is the average refractive index of the fiber. Because of the small modes spacing, several pairs of overlapping signal and idler modes maybe located beneath the bandwidth of the cavity filter. To further suppress the longitudinal modes and increase the longitudinal modes spacing in the signal cavity, a coupled sub-ring cavity with short length is inserted, which is based on Vernier effect^5.

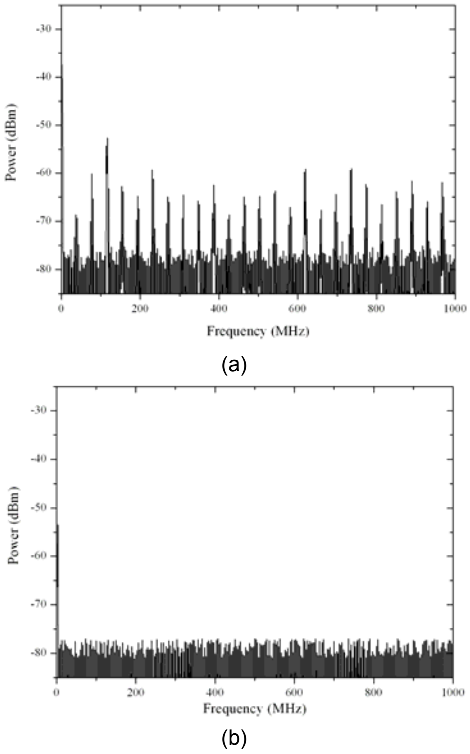

Fig. 2 Measured self-homodyne spectrum: (a) in the singly resonant case with cavities ① and ③ connected; (b) in the doubly resonant case with cavities ①, ② and ③ connected.

The modes spacing is measured by a self-homodyne method, which consists of a photodetector (PD) with 3-dB bandwidth of 20 GHz and a Mach-Zehnder interferometer that includes an optical interferometer with delay time of 3.5 μs in one arm. At first, only the main signal cavity ① is connected, while the sub-ring ③ and idler ② cavities are disconnected. The FSR measured by self-homodyne method is 447 kHz; while the FSR of the idler cavity ② is measured to be 460 kHz. In succession, The FSR of the signal cavity with the sub-ring cavity connected (①+③ connected) is measured. Fig. 3(a) shows its measured beating signal spectrum in a radio frequency (RF) bandwidth of 1 GHz from the electrical spectrum analyzer (ESA). It can be observed that, with the sub-ring cavity inserted, the fundamental beating signal (FSR of the signal cavity) is increased from 447 kHz to 39 MHz. And the fundamental and higher orders beating signal can be observed clearly, while the spectrum is very noisy and unstable owing to the mode hopping. Once the idler cavity is also connected (i.e. cavities ①+②+③ connected), the beating signal disappears and no spike signals are observed, as shown by the detected self-homodyne frequency spectrum in Fig. 3(b). It indicates that a SLM operation with only background noise-limited spectrum up to 1 GHz can be achieved by the proposed technique. The optical spectrum from optical spectral analyzer (OSA) indicates that the oscillating wavelength is 1544.51 nm with a side-mode suppression ratio (SMSR) of larger than 51 dB.

Conclusions

In conclusion, we have presented a SLM fiber OPO. The FOPO is fundamentally structured by resonating independently the nondegenerate signal and idler frequencies in two separate optical cavities, combined with a sub-ring cavity inserted into the signal cavity as a mode-restricting device. The measurement from self-homodyne method shows that the FOPO allows only single-longitudinal-mode to oscillate with SMSR of greater than 51 dB.

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References

1 F Y. Zhou et al. Opt. Lett. 34, 989 (2009).
2 M. E. Marhic et al. Opt. Lett. 27,1439 (2002).
3 S. Yang et al. IEEE J. Sel. Topics Quantum Electron. 15, 393(2009).
4 J. A. Giordmanine et al. Phys. Of Quant. Electron. 31 (1966).
5 Z. Hu et al. Opt. Lett. 25, 469 (2000).