Optics Communications 350 (2015) 154–159

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Performance enhancement of pre-spectrum slicing technique for wavelength conversion

Osayd M. Kharraz [a], Harith Ahmad [b,*], Abu Bakar B. Mohammad [a], David I. Forsyth [a], Mohamad Dernaika [b], Sulaiman W. Harun [b]

[a] Department of Communication Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[b] Photonics Research Centre, Department of Physics, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form
6 March 2015
Accepted 22 March 2015
Available online 24 March 2015

Keywords:
Pre-spectrum slicing
Passive filtering
Gain saturation
Four-wave mixing
All-optical wavelength conversion

ABSTRACT

This paper details a proposal and successful demonstration of an ultra-narrow and very high optical signal-to-noise ratio wavelength converted channel that was generated from an efficient ultra-narrow pre-spectrum sliced probe channel via four-wave mixing in a highly non-linear fiber medium. An array of narrowband fiber Bragg grating filters acted as a discriminative component to pre-spectrum slice the probe channel from backward amplified spontaneous emission, which, in turn, induced an additional fiber Bragg grating filtering mechanism within an erbium-doped fiber medium in a saturable configuration. A resultant optical signal-to-noise ratio of more than 70 dB in the probe channel gave rise to a 40 dB optical signal-to-noise ratio in the converted channel. These outcomes indicate the proposed scheme is highly suitable for practical, cost-effective wavelength conversion in any “pre-spectrum sliced” optical communication system.

1. Introduction

The technique of spectrum slicing (SS) offers a practical means to reduce expenses for future wavelength division multiplexing passive optical networks (WDM PONs) [1]. In this technique, an incoherent broadband light source, such as the amplified spontaneous emission (ASE) from an erbium-doped-fiber amplifier (EDFA), is spectrally “sliced” by multiple band-pass filters in order to generate multi-wavelength channels as optical carriers. The ensuing reliance on a single common light source, as opposed to multiple transmitter lasers operating at different wavelengths, allows for networks with SS-capability to significantly decrease hardware costs and also deliver a robust solution for fiber non-linearities [2]. Recent reports describe ultra-narrow (6 pm) SS systems from incoherent broadband sources transmitting signals in excess of 10 Gb/s over a 20 km length of standard single mode fiber [3–4], while the bit error rate of less than 10^{-4} achieved via the incorporated ultra-narrow band filters has negated the need for a dispersion compensation link [5–7]. Another technique known as “pre-spectrum sliced seed light” (PS-SL) has been proposed to enhance the power efficiency of traditional SS systems [8], whereby EDFA backward ASE is spectrally sliced by a WDM multiplexer and then reflected back by optical mirrors and re-injected into the EDFA. This PS-SL re-injection of spectrum sliced channels allows for considerably better energy efficiency than that afforded by the requisite multiple amplification procedures associated with other SS techniques [3–7].

Future SS and PS-SL systems will inevitably require wavelength conversion. Wavelength blocking across optical connections acts as a limiting factor in current ultra-high speed optical communication networks. The application of all-optical wavelength conversion (AOWC) within WDM networks can overcome wavelength blocking and result in increased network flexibility and capacity [9]. One attractive method of achieving AOWC in optical fibers is via the four-wave mixing (FWM) technique, which provides for fast conversion across a large wavelength span independently of modulation format and bit rate. To date, the FWM technique has been far more extensively studied for expensive coherent systems [10–12] than for cost-effective SS systems, although FWM incorporating incoherent SS light inside non-linear optical fibers has been shown to enhance FWM conversion efficiency [13–15]. An incoherent pump has a large stimulated Brillouin scattering (SBS) threshold in optical fiber, which allows the use of a high power pump to emerge as an option for enhancing FWM conversion

---

* Correspondence to: Photonics Research Centre, University Malaya, 50603 Kuala Lumpur, Malaysia. Fax: +(6) 0379677133.
E-mail address: harith@um.edu.my (H. Ahmad).

http://dx.doi.org/10.1016/j.optcom.2015.03.051
0030-4018/

efficiency. Any FWM that uses present day coherent phase modulation formats is unlikely to achieve satisfactory performance within systems containing broadened pumps [13]. The root cause of this performance issue lies in the fact that each mode of a sliced channel from an ASE source represents a huge number of photons with erratically distributed states of polarization [14]. As such, the temporal fluctuations of phase and state of polarization within incoherent broadened pumps pose a huge challenge to realizing phase modulation formats in spectrum slicing systems. However, the key performance parameter in many optical network systems is optical signal-to-noise ratio (OSNR), and maximizing OSNR in these applications is accordingly prioritized above optimal conversion efficiency [15].

The SS technique involves use of commonly available filters such as arrayed waveguide gratings (AWG), fiber Bragg gratings (FBGs), Fabry–Perot (FP) filters, and thin film dielectric interference filters. These filter technologies, however, are not able to easily provide effective filtering for bandwidths below 0.5 GHz. Filter bandwidths have been shown to be a crucial factor in high-speed spectrum sliced data communications system [3, 4], with narrow bandwidths being more resilient to fiber dispersion and post-narrow optical filtering. Dynamic Bragg gratings, which involve two counter-propagating coherent laser lights via a saturable EDF gain/absorption medium, are highly promising for many potential applications such as tunable filters [16], single longitudinal fiber lasers [17–18], and recently have been applied within adaptive interferometry and fiber sensors [19]. The pre-spectrum slicing technique potentially benefits from using these gratings as an efficient filtering mechanism in order to realize full optical system capacity, and permits a system to dispense with multiple transmitters when using tunable and multiple narrow-band filters. Such systems can henceforth compete with expensive and bulky coherent sources in regards to delivery of large numbers of closely spaced channels in dense wavelength-division multiplexed optical (DWDM) networks.

In this work, we report on the generation of an ultra-narrow and high OSNR wavelength converted channel via FWM in a highly nonlinear fiber medium. The probe signal is shaped from the backward EDFA ASE associated with FBG filters, and its bandwidth is trimmed via a Bragg grating mechanism induced in an EDF medium. Furthermore, the signal is also highly amplified and has a large suppressed ASE level. This paper describes the experimental set-up in section II, results and discussion are given in section III, and finally conclusions are reported in section IV.

2. Experimental set-up

The experimental set-up of the proposed ultra-narrow FWM system is shown in Fig. 1. The rectangular dashed shape illustrates the narrowband filter module configuration used to create the pre-spectrum sliced probe channel and is composed of FBG band-pass filters and a blocker filter. This filter was implemented at the input of EDFA 1 in order to exploit the backward ASE reflections propagating from the left-hand side of the EDFA through circulator 1 port 2 to port 3. The total backward ASE power was 9.15 dBm and circulator 1 insertion loss was 0.5 dB. The backward ASE was then spectrally sliced via the filter module, indicated in the rectangular dashed shape, and the resulting sliced channel emerged from port 3 of circulator 2 with an output power measured as −22.65 dBm. This channel travelled through port 1 of circulator 1 and subsequently experienced amplification in the EDF medium, which manifested as a backward amplified signal upon loop completion through circulator 1 (1→2 ports). This signal achieved a power of −4.04 dBm, due to the benefits associated with the backward ASE amplification properties. The backward amplified signal was then re-injected into the EDFA, so as to induce simultaneous direct interactions with the pumped EDF medium, and all the ensuing EDFA output was transferred into the generated channel with about 20.3 dBm peak power.

The pump signal generated from a tunable laser source was amplified to 19 dBm peak power using EDFA 2. The pre-spectrum sliced probe and the amplified pump channels were both connected to polarization controllers in order to maximize the FWM efficiency, and subsequently combined through a 20/80 coupler. The output port of this coupler was attached to a 100 m long highly nonlinear fiber (HNLF), which acted as the nonlinear medium. This HNLF medium possessed the optical properties highlighted in Table 1, including a high nonlinear coefficient, stable zero dispersion at 1531 nm along the fiber and a small numerical group velocity dispersion across its effective area. A subsequent optical coupler was used to attenuate the high level of output power, with the ensuing FWM spectrum visualized and analyzed via a high-resolution optical spectrum analyzer (HR-OSA) with a resolution of 0.16 pm (APEX AP2051A).

The aforementioned filter module (from AOS GmbH) was able to generate an ultra-narrow linewidth pre-spectrum sliced channel of 7 pm via two stages. The first stage served as a primarily discriminative mechanism utilizing the band-pass FBG filter, which operated similarly to a Fabry–Pérot (F–P) filter to produce a periodic comb of narrow transmission lines, and contained two reflecting filters (i.e. two mirrors) a specific distance apart. A complex reflection coefficient could be acquired by applying a superstructure to the FBGs period and/or phase. Hence, the spectra created were comparable with F–P filters transmission lines, yet their limited spectral wavelength range was not analogous to spectra from classic F–P-filters. Secondly, the blocker FBG had the capability to elect one dedicated line and discard all other lines. An additional filtering mechanism was afforded by means of the sliced channel beating continuously with the counter-propagating backward ASE light and excited transient Bragg gratings, whereby corresponding interactions between light consequently gave rise to dynamic modulation for the EDF refractive index. This dynamic modulation, in turn, allowed for elevated transmission at the excited mode and very large loss in adjacent modes [20], thereby eliminating possible noise and mode hopping in order for an ultra-narrow channel to be successfully generated. The reflection aspect of the blocker FBG filter therefore functioned as a tracking filter which periodically matched the filter center wavelength and routed it towards the output.

While the rectangular dashed shape in Fig. 1 shows the filter module structure, Fig. 2 shows characterizations of the filter module whereby an ASE source was used to provide characterization in terms of linewidth, OSNR and insertion loss. The filter module possessed a centre wavelength of 1555.8 nm, FWHM of 7 pm (871 MHz), approximately 33 dB OSNR transmission and a 5.4 dB insertion loss.

3. Results and discussion

The spectrum in Fig. 3 details the lasing output from EDFA 1 described in the previous section. It can be observed clearly that the scan, which ranges from 1551.5 nm to 1560 nm, has a spectral purity and side mode suppression in excess of 70 dB, while noise levels descend to −75 dBm. Furthermore, the magnified section of the obtained channel (representing a close up at 2 pm/division) allows for observation of the spectrum as being very smooth, ultra-narrow and extremely low in terms of noise.

It is important to note that the spectrum shown in Fig. 3 had a 3 dB linewidth which was narrower than that of the spectrum taken while characterizing the filter module and presented in