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Generation of a 40 GHz pulse stream by pulse multiplication using a sampled fiber Bragg grating

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Abstract: A sinc-sampled fiber Bragg grating is used to achieve multiplication of the repetition rate of a pulse stream from 10 to 40GHz. The spectral characteristics of the grating ensure that the resultant pulses - solitons of 3.4ps width - have the same individual pulse characteristics as those of the input.

Bandwidth limitations imposed by electronically driven devices create the need for the development of new, all-optical techniques for the generation and manipulation of optical signals suitable for repetition rates of the order of 40GHz or higher. In this paper, we demonstrate that optical Fiber Bragg Grating (FBG) technology has developed to the extent that it can be considered a useful tool for such applications. Herein, we concern ourselves with the problem of high frequency pulse train generation, and show that a FBG can be used to coherently manipulate and filter the frequency components of a low frequency pulse stream and transform it into a higher frequency pulse train (at an integer multiple of the initial pulse frequency). In fact we believe pulse multiplication to be just one of a number of optical processing applications of advanced FBG technology- for example we have also demonstrated matched filtering [1], optical code generation and recognition [2], and soliton to square pulse conversion [3].

The principle of our technique is shown in Fig. 1, along with the experimental set up we used in our demonstration. A periodic pulse train in the time domain also has periodic structure in the frequency domain, the period of which is given by the pulse repetition frequency. The relative phases and amplitudes of the infinitely narrow spectral lines are defined by the individual pulse shape. It can thus readily be appreciated that pulse repetition rate multiplication can be achieved by periodically filtering out certain of the spectral components. For example in our case where we multiply up from 10 to 40GHz, we need to filter three out of every four spectral lines leaving a spectrum with 40GHz rather than 10GHz periodicity. In order that the individual pulse parameters are not changed we also need to ensure that the relative phases and amplitudes of the remaining lines are maintained. The required filter thus needs to be periodic with a period matched to the desired final pulse repetition frequency. The individual passbands need to be narrow with good out of channel extinction to give adequate discrimination between adjacent lines of the initial spectrum, and the overall envelope response needs to have a square envelope and a suitably periodic phase response. These are pretty stringent filter requirements but ones that can be met using the latest superstructure FBG technology. Note that this is a purely passive, all-optical technique and can in principle be used with any suitably periodic pulse source. This is to be contrasted to previous repetition rate multiplication schemes which have either incorporated Fabry-Perot filters within laser cavities to provide intracavity mode selection [4], or have been based on the rational mode-locking technique [5]. These techniques in fact do not really perform true optical multiplication in the sense that they serve to allow the use of lower frequency optoelectronic components at higher frequencies and are therefore of more restricted functionality and applicability.

The approach used to obtain such complex FBG structures is known as the superstructure (or sampled) grating technique [6]. Superstructure gratings are obtained by imposing a slowly varying amplitude/phase modulation (on the rapidly varying) refractive index profile of an otherwise uniform grating. In general, for gratings in which the optical signal penetrates the entire grating length without significant attenuation, it can be readily shown that the frequency response of the FBG is given by the Fourier transform of the spatial refractive index modulation profile. We have developed a continuous grating writing technique that effectively writes Bragg gratings on a grating plane by grating plane basis. Full control of the grating apodization and phase profile can therefore be achieved by dephasing subsequent grating planes with respect to each other. In this way the effective refractive index modulation is changed, whilst the average background index is kept constant. The quality of the writing process is such that we can maintain the coherence of the grating writing process over 10's of cm's length scales. We can thus write FBG's of almost arbitrarily complex spectral response. The capability to design such complex gratings has been demonstrated in the past [6 - 8]. In Ref.[7] we first reported the design and fabrication of sampled FBG's with spectral responses similar to the one used in this experiment.

In the work presented here we demonstrate pulse multiplication from 10 to 40GHz. The original 10GHz pulse train was generated by a harmonically mode-locked erbium-fiber, soliton ring laser [9]. The laser generated close to transform-limited soliton pulses of 3.4ps (see Fig. 4a). The central wavelength of the laser could be finely tuned using an intracavity filter (6nm bandwidth), and the pulse repetition rate adjusted in steps of ~350kHz, i.e. the harmonic spacing of the laser. The pulse spectrum is shown in Fig. 5a, and in accordance with Fourier theory, consists of narrow spectral lines separated by 10GHz. The shape of the spectral envelope is simply that corresponding to the individual soliton pulses, and has a 3dB width of 0.85nm. The –30dB spectral width of the pulses is ~ 4nm. The pulses were launched onto the pulse multiplication grating using a fiberized optical circulator. The grating was mounted within a mechanical rig that allowed strain tuning of the spectral response relative to the laser.

The spectral response of the grating that we fabricated to perform the pulse multiplication is shown in Fig. 2b. The individual passbands are separated by 40GHz (0.32nm), and have a 3dB width of 5GHz. Note the rapid roll-off in the reflectivity of the individual passbands; the filter suppression between the reflected spectral peaks and their adjacent 10GHz spectral lines is ~ 25dB. The filter has 20 passbands and a corresponding bandwidth of 6.4nm - more than adequate to accommodate the full spectral bandwidth of the pulses. The grating was 50mm long and each channel had a peak reflectivity of ~ 10%, limited by the available refractive index modulation from the fiber used. Using a sufficiently photosensitive fiber, similar gratings with reflectivity as high as 90% have previously been fabricated [7]. The actual refractive index superstructure profile used to write this grating is shown in Fig. 2a, highlighting the precision required of the grating writing process. The spacing of the individual maxima in the modulation profile define the spectral period of the filter, and the number of channels is given by the ratio between the width of the spatial features and their period [7]. The spatial profile of the individual grating samples follows a *sinc* form ensuring that the reflectivity envelope is square as required. The overall length of the grating and the apodization profile of the structure, in this case a Blackman profile, define the bandwidth and the high sidelobe suppression for the individual spectral passbands respectively.

Obviously in order to obtain optimum pulse multiplication and to avoid significant pulse distortion the appropriate phase relation needs to be maintained between the individual spectral components after reflection from the grating. If the grating response is truly ideal, the spectral periodicity of the source is matched to the channel spacing, and the pulse spectral lines are centered within the channel passbands, then this will be the case. However, in reality imperfect matching of the grating period, the pulse central wavelength to the grating passbands, and the phase noise due to the (small) grating writing inaccuracies (caused mainly by variations in the fiber core diameter [10]) result in deviations from this idealized case. In order to assess the likely impact of these issues we have simulated the system and examined the sensitivity to period mismatch, wavelength detuning and the observed grating phase errors. We have found the system to be reasonably robust on all counts. For example, in Fig. 3 we show the result of reflecting 10GHz, ~3.4ps soliton pulses from the grating structure shown in Fig. 2 for a variety of tuning conditions. It is seen that the spectral lines have to be detuned by ~ 1.3GHz from the FBG channels, or the repetition rate of the source has to be detuned by ~ 0.3GHz from the nominal FBG spacing, in order to experience a 3dB degradation of the output signal power. Even in these extreme detuning circumstances the actual pulse distortion itself is still not severe, allowing good long-term stability of the output signal without any need for active stabilization of the FBG.

In Fig. 4 we plot the autocorrelation trace and spectrum of the incident 10GHz and reflected 40GHz pulse train under optimal tuning conditions. The original pulses (Fig. 4a) have a width of 3.4ps and time-bandwidth product of 0.358, indicating almost transform-limited solitons. The output pulses are shown in Fig. 4b. The period of the pulse stream is now 25ps, corresponding to a repetition rate of 40GHz, whilst the pulse width has remained unaffected. Note the flat background between pulses which indicates the absence of any significant pedestal element. The filtering action of the FBG can be clearly seen in Fig. 5, where the spectra of the original and the filtered pulses are compared: three out of every four spectral lines have been filtered out, down to ~ -18dB level relative to the 40GHz components using the current grating, although we consider that this could be further improved upon. The envelope of the reflected signal remains essentially the same as that of the input; pulse quality is thus indeed seen to be preserved. We investigated the system performance under a variety of repetition rate, and central wavelength detunings and confirmed that the performance was reasonably tolerant to both as predicted by the numerics.

In conclusion, we have experimentally demonstrated the generation of a 40GHz pulse stream, by passive all-optical filtering of the spectrum of 10GHz pulses, using a sinc-sampled FBG. The technique provides a simple, convenient way to obtain trains of high-frequency pulses at precise multiples of a lower, more readily derivable pulse repetition rate. Note that it allows for higher values of multiplication factor than we have demonstrated herein, and is limited primarily by the duration of the input pulse stream rather than the grating technology itself. The results highlight the recent advances in grating fabrication technology, which now allows the fabrication of truly complex optical filters with almost arbitrary amplitude and phase response. We believe such components have great potential for coherent pulse shaping applications and could find a variety of uses in future high-speed communication systems and optical processing systems.

Figure captions

Fig. 1 Schematic and principle of operation.

Fig. 2 (a) Profile of the refractive index, and (b) spectral response of the superstructure FBG used for pulse multiplication (resolution = 80pm).

Fig. 3 Simulation results showing the output pulses with (a) the FBG correctly tuned to the source, (b) the FBG channel peaks detuned by 1.3GHz from the source's spectral lines, and (c) the repetition rate of the source detuned by 0.3GHz from the FBG channel spacing.

Fig. 4 Autocorrelation traces of (a) the 10GHz input pulses, and (b) the 40GHz output pulses.

Fig. 5 Optical spectra of (a) the 10GHz input pulses, and (b) the 40GHz output pulses (resolution = 20pm).

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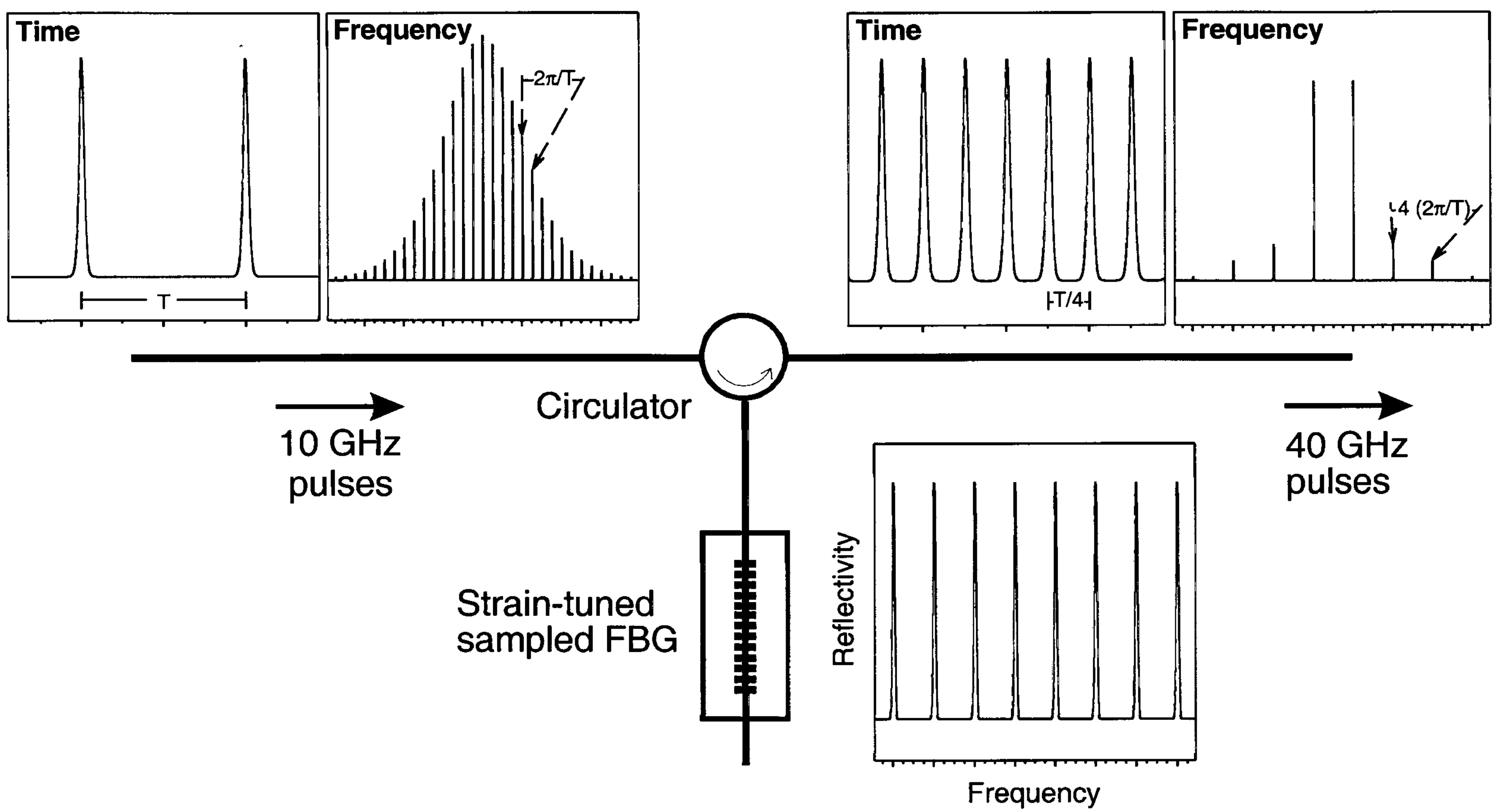
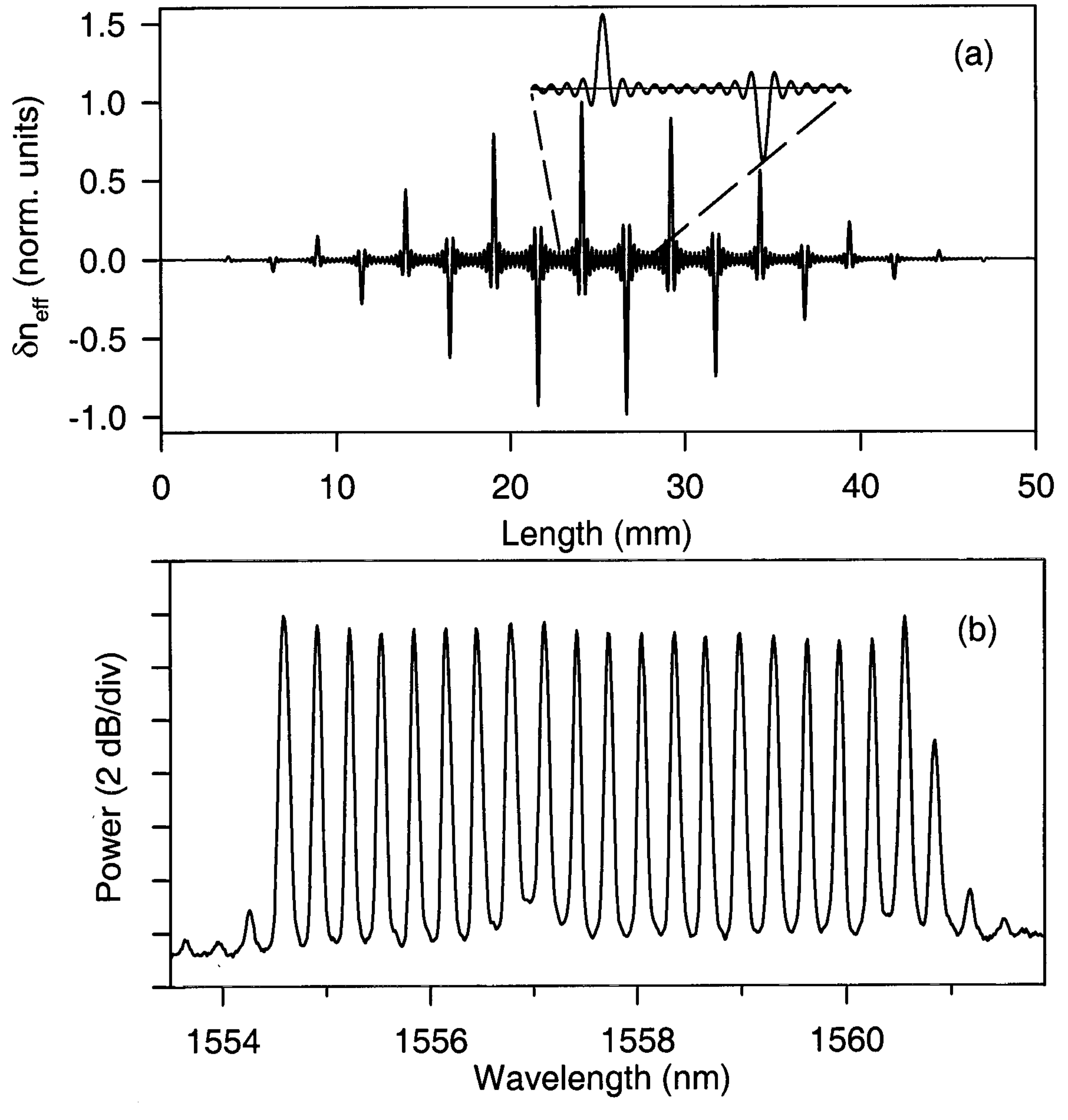

Time
T
Frequency
2π/T
Time
T/4
Frequency
4 (2π/T)
Circulator
10 GHz
pulses
40 GHz
pulses
Strain-tuned
sampled FBG
Reflectivity
Frequency

Fig 1



(a)
δn_eff (norm. units)
1.5
1.0
0.5
0.0
-0.5
-1.0
0
10
20
30
40
50
Length (mm)
(b)
Power (2 dB/div)
1554
1556
1558
1560
Wavelength (nm)

Fig. 2

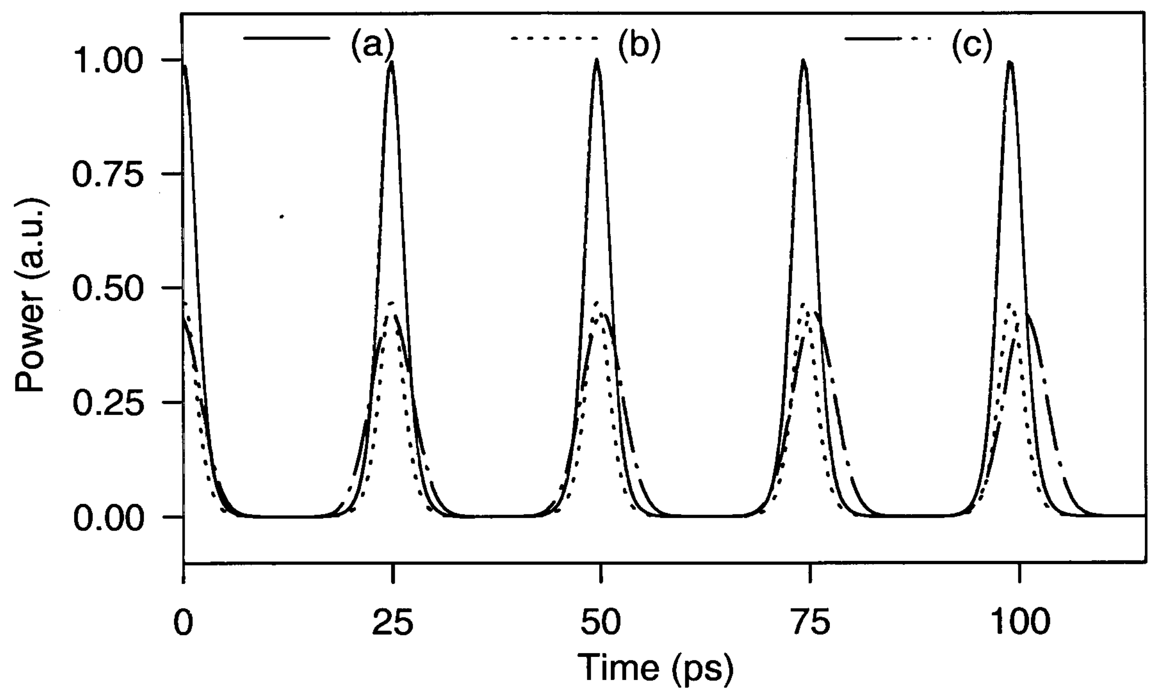


Fig. 3

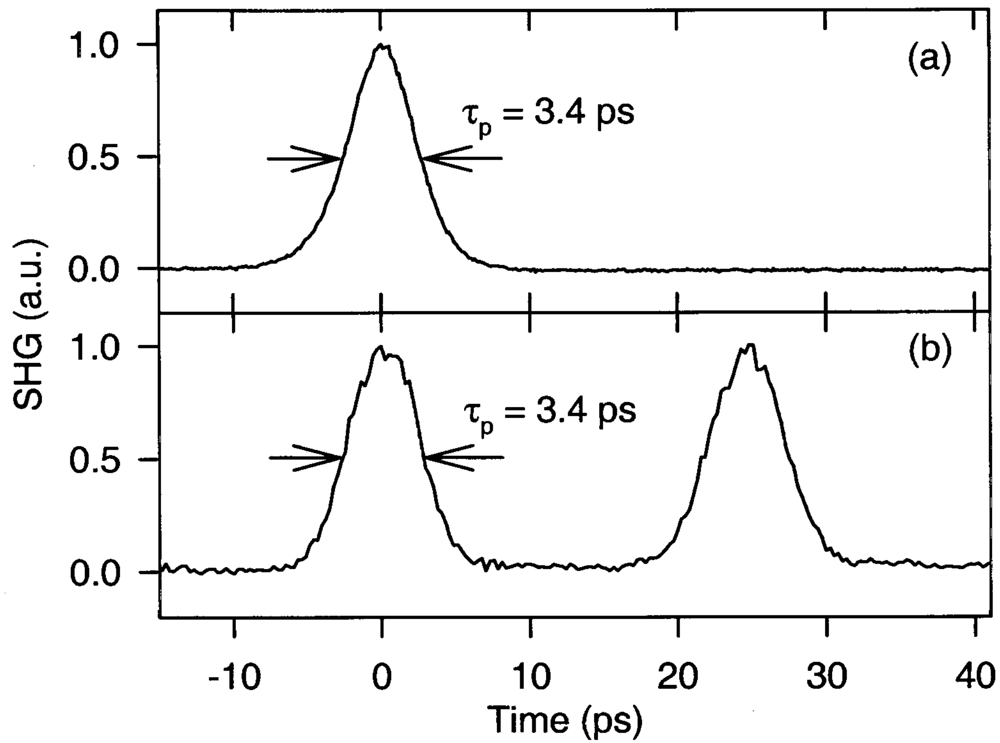


Fig. 4

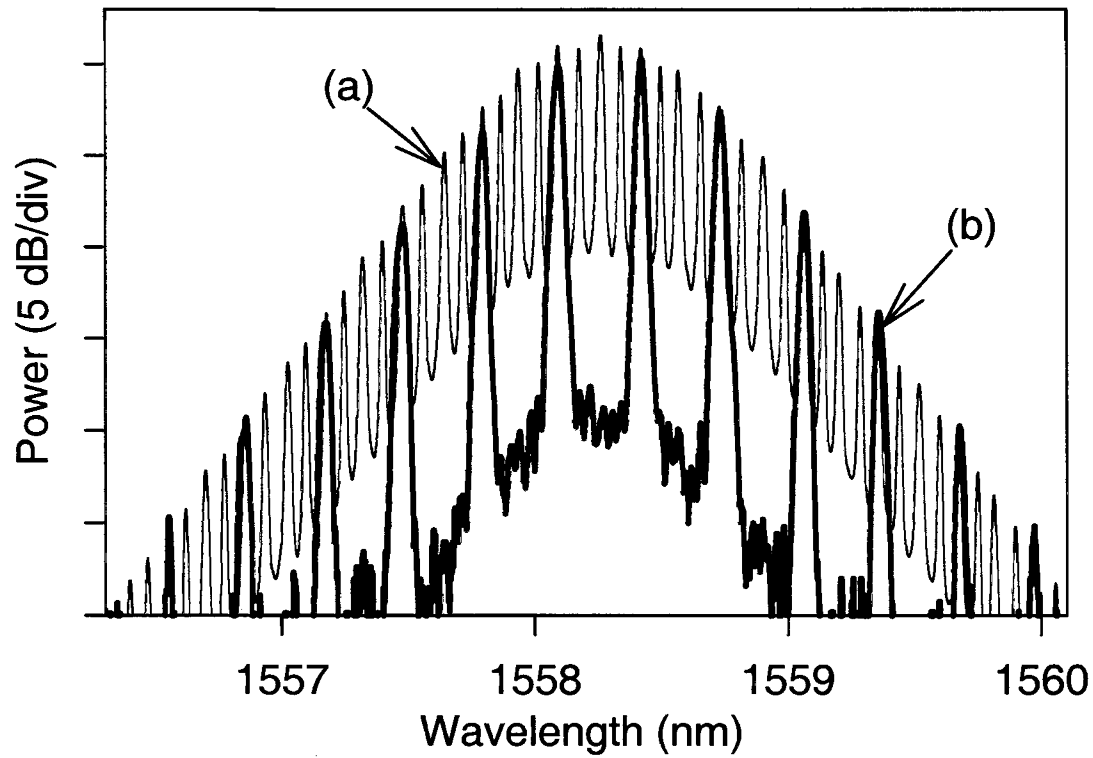


Fig. 5