270-km 10 Gbit/s WDM dispersion compensation using a chirped AWGM

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Abstract: We show that a 10-Gbit/s per channel SM-fiber WDM system could be extended from 70 km to 270 km using a Array-Waveguide Multiplexer (AWGM) with a quadratic phase shift added across waveguide array.

Introduction: Array-Waveguide Grating Multiplexer/Routers (AWGMs) offer useful functionality as add-drop multiplexers, multiplexers/demultiplexers and wavelength routers [1,2]. Recently, their advantage of having zero dispersion, due to their symmetrical impulse response, hence linear phase, has been recognised [3,4]. We propose a modification to the standard design of the AWGM which allows it to be used as a multi-channel dispersion-compensator with an ability to compensate for over 270 km of standard fiber. We used numerical simulations to prove its performance. Furthermore, our AWGM design can simultaneously be used to multiplex or demultiplex optical channels, and can be used to compensate multiple fibers using a single device, or can be used to compensate for longer fiber spans using multiple parallel passes through it.

Theory: The Arrayed-Waveguide Grating Router/Multiplexer (AWGM) relies on planar couplers linked by optical delay lines. The AWGM can be thought of as a finite-impulse response transversal filter (similar to a digital filter), if a single input and output is considered [4]. As shown in Figure 1, the first Free-Propagation Region (actually a multi-moded planar waveguide) distributes power between the Array Waveguide delays; the second coupler combines the powers of these waveguides, and forms an interference pattern on the Output Waveguides. Changing the input wavelength sweeps the interference pattern across the output waveguides, and the coupling can be calculated using overlap integrals [5].

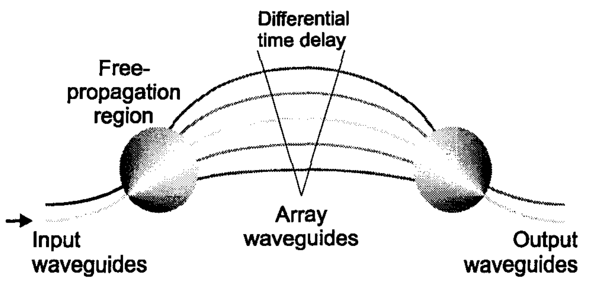

Figure 1: Simplified schematic of an AWGM/AWGR showing the distribution of power from the active Input Waveguide (arrowed) to the Array Waveguides, which act as delays. If the AWGM is unchirped, the outputs of the Array Waveguides will constructively interfere at one Output Waveguide at frequencies separated by the free spectral range.

For a multiple-output AWGM, the phase shift across the input and output couplers to the individual outputs will be different for each output. This will mean that constructive interference between the Array Waveguide delay lines will occur at slightly different frequencies for the outputs. Thus each output will have its peak response at a slightly different frequency. To fractionally shift the passbands, for example, to align the filter with a source, phase advances, $\theta(i)$ can be applied across the array waveguides [6]. These phase advances have insignificant time delays associated with them, but are implemented by fractionally shortening the guides, for example. A linear increase in phase advance with guide number (i) will tune the passbands to shorter wavelengths without altering the passband shape. A quadratic phase advance with guide number causes a widening of the passbands [7], as the contribution to the passband from any two adjacent guides is dependent on the phase difference between the two guides. We show numerically that this 'chirping' can be used for dispersion compensation. An additional cubic phase advance distorts the shape of the passbands and can be used to compensate for higher-order dispersion, and thus may be useful for pulse compression.

By implementing a (quadratic) phase advance across the Array Waveguides proportional to the square of the guide number (with i=1, the shortest waveguide, having zero phase advance), we can design a dispersion compensator/demultiplexer. This device works if the Input Waveguide has a sufficiently wide far field to excite many of the Array Waveguides. The shorter Array Waveguides will only focus the lower optical frequencies on the Output Waveguide. However, because of their decreased *differential* phase delays the longer waveguides will focus the higher frequencies on the output waveguide. Thus the higher (bluer) frequencies will suffer the greatest absolute delay, compensating for the opposite characteristic in most optical fibers at 1550 nm.

The maximum dispersion that the AWGM can compensate (s/Hz) can be found by considering the change in delay time with optical frequency, and is:

$$\beta_2 L = (1/4\pi).\ (T_1)^2/(T_2.f_0)$$

where: T_1 represents the mean difference in time delays between the waveguides, which is the inverse of the free-spectral range (FSR) of the AWGM, T_2 represents the delay required to implement quadratic phase advance between the i=1 and i=2 guides (normally negative), and f_0 is the optical frequency. To increase the magnitude of the dispersion compensation requires a *reduction* in the magnitude of the quadratic chirp across the waveguides, and a reduction in FSR.

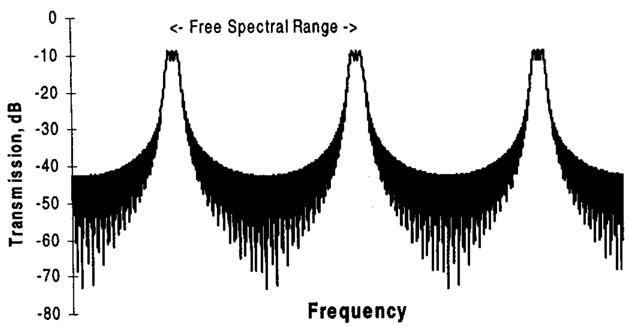

Fig. 2: 121-Guide AWGM response with Gaussian power distribution and chirp

AWGM Simulation: We used a commercial simulator, GOLD [8], to simulate the AWGM. Fig. 2 shows the optical frequency response of a 121-guide AWGM with a free-spectral range of 200 GHz (T_1=5 ps) and a Gaussian power distribution across the guides designed to give a 0.5-GHz FWHM passband *before* chirping. The narrow passband before chirping implies that most of the arrayed waveguides are illuminated by the arrayed waveguide. A chirp of $T_2 f_0$ = -3.8x10^{-4} was used giving $\beta_2 L$ = -5241 ps^2, which broadens the passbands to 14 GHz FWHM ,which is close to the minimum optical bandwidth for 10-Gbit/s transmission. Wider passbands can be obtained by using more guides and chirp.

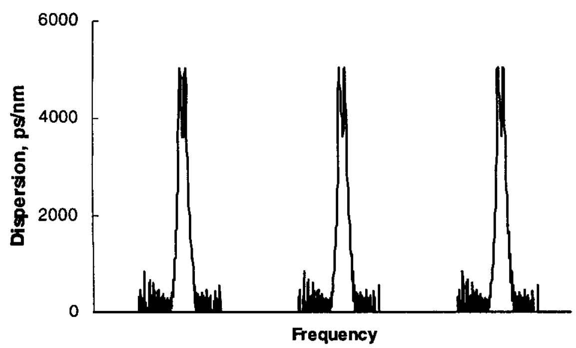

Fig. 3: Dispersion that can be compensated (ps/nm) by the AWGM versus optical frequency. Free spectral range = 200GHz.

Fig. 3 shows the dispersion compensation ability *converted to ps/nm* versus frequency for these parameter values. The AWGM can compensate for a large, but relatively constant, amount of dispersion over each of its spectral passbands, and thus could be used to compensate a number of wavelength channels. The compensation available is around 4300 ps/nm within the passbands. This allows the compensation of 270 km of fiber with a dispersion of 16 ps/nm/km. The dispersion characteristic can be flattened by widening the passbands by increasing the chirp, or by increasing the unchirped bandwidth so that fewer guides are illuminated, making the illumination strongly apodised.

System Simulation: To demonstrate the effectiveness of dispersion compensation we simulated an optical communication system using standard single-mode fiber which has a dispersion of 16 ps/nm/km at 1550 nm. The system transmitted 10-Gbit/s non-return-to-zero data using an externally-modulated (dynamic chirp free) source. The power penalty measured from eye closure (increase in received power required to compensate for dispersion) versus the transmission distance, equal to the length of the fiber, is shown in Fig. 4 for Compensated and Uncompensated systems. For uncompensated systems, the power penalty increases as the fiber length is increased and becomes unacceptable (approximately greater than 2 dB penalty) for lengths beyond approximately 90 km. The proposed device allows systems of a far greater length to be used by compensating the dispersion of the fiber. For this

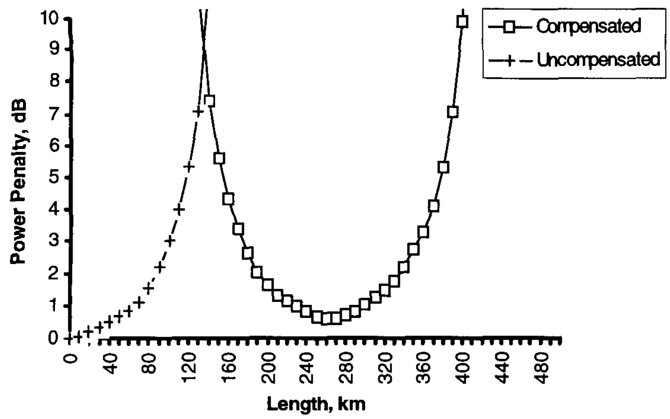

Fig. 4: Power penalty due to dispersion versus fiber length

particular design, the dispersion of 270-km of fiber is compensated for by the device. The residual eye penalty is due to the narrow bandwidth of the AWGM passbands. For shorter systems, the device overcompensates for the fiber's dispersion, leading to a penalty.

The eye diagram for a 270-km compensated system is show in Fig. 5. The eye diagram is almost completely open (<1-dB penalty), with good differentiation between zero and one bits over a wide range of timings. Note that the power scale is arbitrary as it is assumed that optical losses can be compensated for by amplification.

This design requires differential delays of 5 ps between the guides and 121 guides. Thus the longest guide should provide 600 ps greater delay longer than the shortest. With Indium-Phosphide circuits (InP) this means a path length difference of less than 4 cm, equivalent to a semi-circle of 1.2-cm radius. Thus the device could be integrated onto a standard wafer of InP, and so compact temperature-stable and mechanically- stable devices could be produced.

Greater compensation could be obtained by looping back the AWGM's output to another input/output to give multiple passes through a single AWGM.

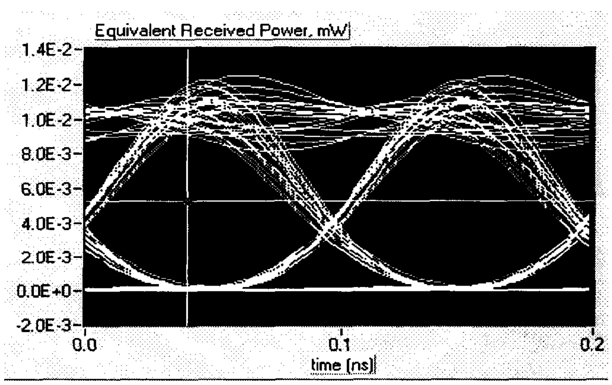

Fig.5: Eye diagram for a 270-km compensated system with the optimum sampling point indicated

Conclusions: Although an AWGM is usually non-dispersive, due to its symmetrical impulse response, we have demonstrated that a chirped AWGM could be a very effective multi-WDM-channel dispersion compensator by modelling the eye closure of a 10-Gbit/s lightwave system. The system length for a 1-dB penalty was increased by over 200 km, to 270 km.

In conclusion, AWGM's could contend with fibers and Bragg gratings for dispersion compensation, with the added benefit of their wavelength-routing and multi-channel capabilities. However some power loss will always accompany the dispersion compensation function in AWGMs.

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8 Gigabit Optical Link Designer (GOLD) is a commercial product of Virtual Photonics Pty Ltd, Australia, (info@vp.com.au, www.vp.com.au) and was developed in conjunction with the Australian Photonics Cooperative Research Centre and Telstra.