WDM CHANNEL MANAGEMENT USING PROGRAMMABLE HOLOGRAPHIC ELEMENTS

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We describe results of a high-resolution (0.8nm) holographic, digital multi-wavelength filter, based on a ferroelectric liquid crystal (FLC) spatial light modulator (SLM). The filter has applications as a wavelength-division-multiplexing (WDM) technology for use in optical telecommunications. The polarisation-insensitive FLC SLM acting as a programmable holographic element in conjunction with a highly wavelength-dispersive fixed diffractive element has been used to perform a number of important WDM functions: Demultiplexing of single and multiple (up to 4), segmented passbands spaced by 0.8nm, and dynamic erbium-doped fibre ampifier (EDFA) gain equalisation. Apodisation of the filter passband has been demonstrated, and optical add/drop multiplexing is also possible using the holographic technique. The filter offers potential low loss, excellent crosstalk characterisitcs, and a high resolution over a large tuning range.

Introduction

The development of the erbium-doped fibre amplifier (EDFA) [1] has opened up the possibility of very high bandwidth data pipes, for example by using WDM [2], as well as allowing new optically transparent architectures, such as wavelength-routed networks [3]. These new systems require specialised functional components, such as tunable sources, receivers, switches and routers, reconfigurable optical amplifiers and wavelength converters. Optical telecommunications networks require components which are optically transparent and polarisation-insensitive, have a low crosstalk and low loss, achieve high resolution tuning, are compact and operate at low powers. In this paper we describe how holographic filtering already satisfies most of these demands, and is becoming increasingly attractive as a polarisation-insensitive [4] WDM technology for active channel management [5,6]. To date, holographic filtering has been used to demonstrate 4, 6 and 8 WDM channel equalisation spaced by 4nm [6,7,8]. However, by using a high-spatial frequency (300 lines/mm) blazed grating, a resolution of 0.22nm has been achieved, which allows the filter to manage WDM channels spaced by the ITU 0.8nm standard.

Holographic Filter Operation

The operation of the high-resolution tunable holographic wavelength filter, shown schematically in figure 1, is based on the wavelength-dispersive nature of diffraction gratings. On its own, the SLM pixel pitch (165μm) is too large for useful tuning to be obtained. However, a fixed blazed diffraction grating of high spatial frequency (300 lines/mm, i.e. line-pair width of 6.66μm) used in conjunction with the SLM yields a compact high resolution filter. The use of an electrically addressed SLM (EASLM), to display a desired phase pattern, provides a programmable grating (*i.e.* a hologram) whose spatial period can be altered at will. In addition, holograms can be designed to have multiple spatial periods, to allow multiple wavelength tuning. A lens placed after the SLM and fixed diffraction grating converts the angular separation of wavelengths to a spatial separation, and a single-moded (SM) optical fibre acts as a fixed spatial filter to select the desired wavelengths.

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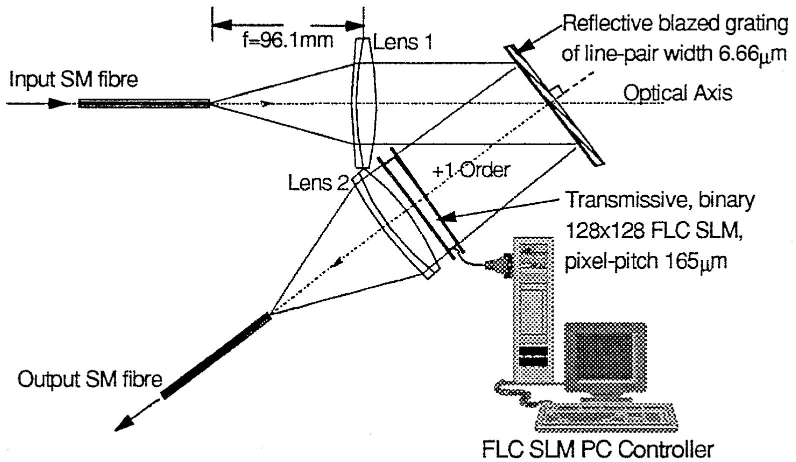

Figure 1: Schematic diagram of polarisation-insensitive holographic wavelength filter

Tunable Holographic Wavelength Filter

The current filter has a tuning range of 12.4nm in steps averaging 0.22nm, with a 3dB passband of 0.34nm, and is polarisation-insensitive. Figure 2 shows the spectral profile of the filter transmission using a hologram (a). Without apodisation, it is close to Gaussian in shape. However, beyond 0.66nm either side of the centre

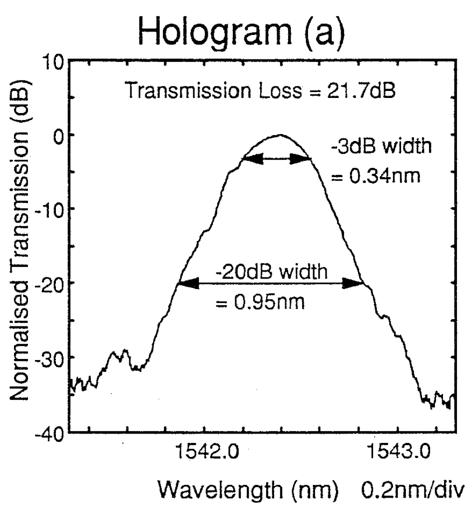

Figure 2: Logarithmic plot of filter passband with FWHM=0.34nm

wavelength, the filter extremities depart from Gaussian behaviour and has the larger 'tails', as illustrated in the figure, of a Bessel function, which converges to zero more slowly than a Gaussian. The diagram shows that the filter has an optical signal-to-noise ratio, SNR >30dB. However, this is only achieved for wavelengths greater than ~0.7nm away from the central wavelength, owing to the convolution arising from the Gaussian/Bessel coupling efficiency into the fibre end. The 21.7dB loss of the filter is accounted for in the following table:

SLM Losses	**dB**
FLC switching angle (2θ=28°)	6.57
Diffraction efficiency (η=36.5%)	4.38
Aperturing of SLM	0.79
Blazed Grating Losses	
Diffraction efficiency (η=~65%)	1.90
Phase depth optimised for λ=1μm	1.43
Sundry Losses	
10 reflecting surfaces, each contributing 4% loss	1.77
FC/PC patchcord uniter losses (×2)	1.14
fibre/lens coupling efficiency (~42%)	3.72
TOTAL	**21.7**

Optimisation of the FLC and optical components, use of a 1.55μm blazed grating and careful design should allow a total optical loss of only ~7dB.

Since the FLC is not fully bistable it is necessary to periodically update all the pixels, with the frame being downloaded row by row. A practical device, however, would make use of either a bistable FLC or an alternative addressing scheme, removing the need for the update process other than when changing between different holograms. The effect of the periodic updating is to cause a small modulation during normal transmission of approximately 0.035dB. This is illustrated in Figure 3. The ~1dB loss of the signal that occurs during the periodic frame update is undesirable, but new pixel addressing schemes currently under development for silicon backplane FLC SLMs should eliminate the need for this process, even with an FLC material that is not fully bistable. A fully bistable FLC used within the SLM would avoid all temporal modulation of the light and also allow fail-safe operation of the device. In the event of a power failure, the SLM would still continue to diffract the light and the device still operate, albeit without reconfigurability.

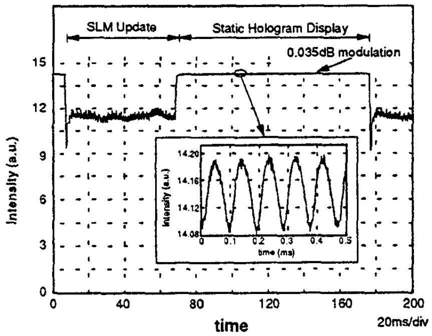

Figure 3: Temporal modulation of filtered light

Passband Apodisation

The Gaussian spectral-profile may be tailored to achieve a more apodised, passband-flattened response, by modifying the hologram. This is shown in figure 4, which shows the normalised transmission characteristic for a different hologram (b). The -3dB width is now 0.59nm, increasing to 1.35nm at -20dB, i.e. a more rectangular response. This is at the expense of an additional 2.3dB loss, and a reduction in the noise suppression to 18 dB.

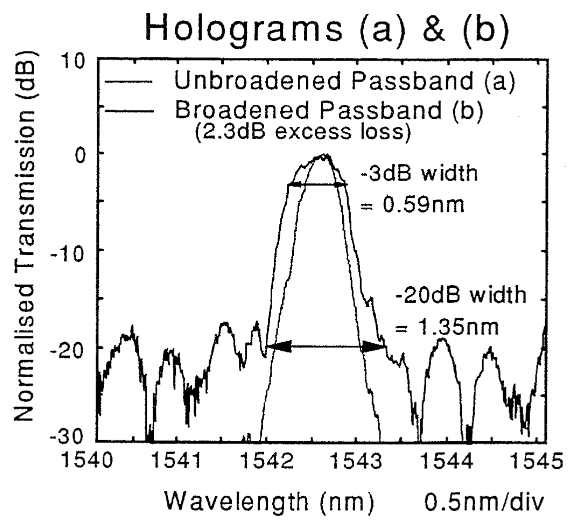

Figure 4: Holographic Filter Passband Apodisation

EDFA Gain Equalisation

Multiple wavelength filtering is one of the distinguishing features of holographic wavelength filtering and is important for WDM demultiplexing and EDFA gain equalisation. Figure 5 shows the transmission of four passbands separated by about 0.8nm. The 3dB width of each passband is still about 0.34nm, and noise supression is generally substantially greater than 8dB, with inter-channel ASE suppression reaching 20dB. Passband uniformity is within 2dB. There is an associated higher loss due to the available light being divided into 4 passbands, and the reduced diffraction efficiency of binary-phase holograms when they function to fan-out light. The average optical *SNR* or channel isolation for a binary hologram is proportional to the number of hologram pixels *N*, and inversely proportional to the number of filtered channels *C*, such that:

$$SNR \geq \frac{N}{2C} \tag{1}$$

Thus the SNR performance of a hologram reduces as it is required to control more channels, but improves with more pixels. Likewise, binary-phase holograms show an additional transmission loss of $\sim 10\log_{10}(C)$, when filtering *C* channels [9], hence the 7.3dB excess loss when filtering 4 channels.

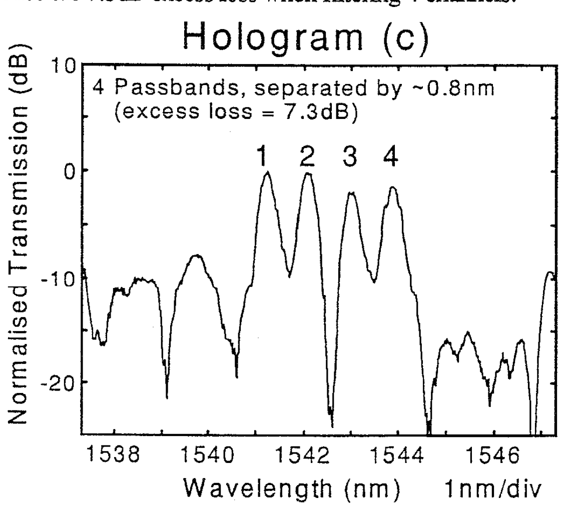

Figure 5: Filtering of 4 WDM channels spaced by 0.8nm

Tunable Fibre Laser

Tunable fibre lasers may potentially serve an important function in WDM telecommunications networks, acting as stable and pure laser sources. They have a very narrow linewidth, high output powers and large tuning ranges. We have already published the results of a tunable erbium-doped fibre laser [10], tuned using a holographic wavelength filter. The holographic filter and a high-gain EDFA were placed within a unidirectional fibre ring-resonator. A 3dB coupler was used to access the output power. Tuning over 38.5nm, in the range 1528.6-1567.1nm with steps of 1.3nm was achieved, with output powers of up to -13dBm. The inherent EDFL 3dB lasing linewidth was found to be of the order of 3kHz, and the long term wavelength stability was about 0.1nm. A hologram with a mixed spatial frequency has also been designed to allow the EDFL to simultaneously lase at 1562.5nm and 1556.0nm, as shown in Figure 6. Due to the gain medium being relatively homogeneous and dependent at the two wavelengths, mode competition means that the lasing mode powers fluctuated considerably. The power in each mode is also considerably lower than usual, since only half the EDFA power is available to each mode, the hologram has less than half the usual diffraction efficiency for each of the two wavelengths, and a 10/90 coupler is used for the laser output.

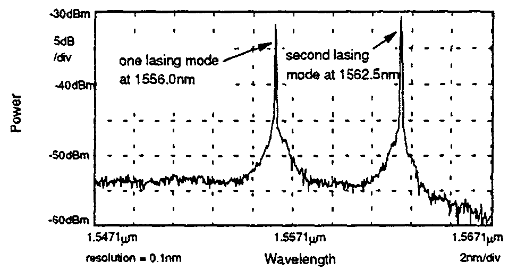

Figure 6: Multiple lasing wavelengths

Future Work

The currently unused extra dimension of the SLM can also be used to add functionality, such as in a space-wavelength switch. This could serve as an add-drop multiplexer (ADM) in dynamic wavelength-routed optical networks. Figure 7 shows an 'exploded' concept for a polarisation-insensitive, optically transparent, compact, low-loss space-wavelength switch, using a reflective FLC SLM. The switch acts as a 3×3 fibre cross-connect, which can also perfectly shuffle wavelengths between the various fibres. The integrated design incorporates a graded-index (GRIN) lens instead of a bulk refractive lens, but the limited numerical aperture of a GRIN lens will tend to limit the number of fibres possible to interconnect. Figure 8 shows how the packaged, integrated device might look.

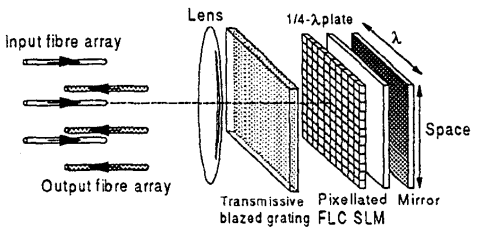

Figure 7: 'Exploded' 3×3 space-wavelength switch

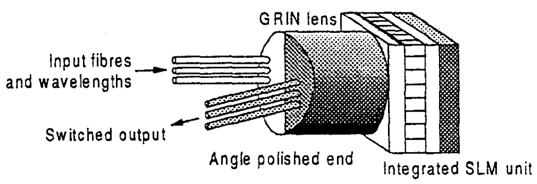

Figure 8: Packaged, integrated space-λ switch

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