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# FIBRE-BASED NARROWBAND OPTICAL FILTERS AND SOURCES

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## Introduction

Optical filtering is perhaps one of the most basic signal-processing functions and consequently finds a wide variety of applications throughout the field of optical telecommunications, sensing and signal processing. With the growing complexity of fibre circuitry, the fibre-based filter has become increasingly-important with its obvious advantages of compatibility and low interconnection loss. Over the years numerous relatively-broadband fibre filters have been developed for applications which require filtering of widely-separated wavelength channels, mostly based on some form of intermodal interference (e.g. twin-core, birefringent, or interferometric devices). More recently, interest in coherent transmission and fine-grain wavelength-division-multiplexed (WDM) systems (which require sub-megahertz laser linewidth and channel spacings of a few gigahertz) has emphasised the need for narrowband fibre filters with linewidths of less than 1nm.

## Narrowband Fibre Filters

Three main narrowband filter types have emerged with quite different characteristics. These are the fibre relief grating[1], photorefractive Bragg grating[2] and the miniature fibre Fabry-Perot (FFP)[3]. Although not strictly narrowband, the simple in-line, multi-layer dielectric chip[4] should not be ignored for its potential. Also, for pure simplicity and low cost, the rare-earth-doped fibre absorption filter[5] is hard to match.

***Fibre Relief Grating Filters.*** So called because they apply a physical corregation on the side of the fibre, fibre relief gratings are made by polishing the fibre cladding to obtain access to the core evanescent field, or employing a D-section fibre. Photoresist is then applied and exposed holographically using a short-wavelength laser. A grating is then etched into the fibre using either a dry or wet process. A high-index layer is then normally applied to "lift" the field and optimise its interaction with the grating corregations.

Fibre relief gratings act either as a narrowband Bragg reflector, or as a band edge filter[6] in transmission. The latter characteristic is caused by radiation through the grating of wavelengths shorter than the Bragg-resonance, while longer wavelengths are transmitted. Reflectivities as high as 95% with a bandwidth between 25 and 1800GHz have been reported[7]. Excess losses are low (< 0.5dB) and limited tunability (3nm) can be obtained by temperature tuning or changing the index of the grating overlay.

***Photorefractive Bragg Gratings.*** An exciting recent development is the technique of directly writing photorefractive Bragg gratings within the core of a single-mode fibre[2]. An interference pattern of ultraviolet light at around 240nm is focussed onto the core of a germanium-doped silica fibre. After exposure for a few minutes, a distributed Bragg reflector is created at a wavelength corresponding to the periodicity of the interference pattern. Using this transverse holographic technique, photorefractive gratings can be written at any wavelength and can have reflectivities up to 98%. The origin of the effect is the subject of much controversy, with several theories available. There appears to be agreement that it is associated with GeE' centres within the core which absorb strongly at 240nm. However, writing of the gratings is accompanied by an increase in absorption of only 0.2% at 1.55$\mu$m.

Unlike fibre relief gratings, photorefractive gratings act as a bandstop filter, reflecting the stopped light, and transmitting all else. Reflection linewidths of 20-100GHz are obtainable and the filters exhibit limited tunability (2nm) using either temperature or strain[8]. The main appeal of photorefractive grating filters is the ease with which they can be made, their very low loss and the non-invasive nature of the fabrication process.

***Miniature Fibre Fabry-Perot Filters.*** Fibre Fabry-Perot filters[9] have been around for a number of years, but have recently come to prominence with the development of widely-tunable commercial devices. Several configurations are possible, the most popular being to deposit highly-reflective multi-layer dielectric mirrors on the ends of a short (< 2mm) stub of fibre which is then glue-spliced between fibre pigtails. Tuning is achieved by piezoelectrically stretching the short fibre length, which incorporates a gap for this purpose. The inclusion of a fibre waveguide within the Fabry-Perot resonator is crucial, since it prevents beam walk-off and allows a high-finesse ( > 100) to be achieved in a compact, robust device.

FP filters differ from grating filters in that they have a bandpass characteristic, reflecting the stopped light. In common with all Fabry-Perots, they exhibit multiple passbands, with typical bandwidths of 1-100GHz and a free spectral range (FSR) of 100-100,000GHz. Excess losses are < 3dB and tunability over one or more FSR is possible[10].

## Tunable Single-Frequency Fibre Lasers

Apart from their general telecommunications use, fibre narrowband filters have a major role in the development of tunable, single-frequency fibre lasers where they act as a frequency-selective element in the laser resonator. All three filter types have been used[11,12,13], with fibre Bragg gratings acting as frequency-selective reflectors, while FFP's are employed as bandpass filters in ring resonators.

Obtaining single-frequency operation of a fibre laser requires the selection of one of many very closely-spaced axial laser modes. Two approaches can be taken: (1) the use of a short Fabry-Perot resonator to space the axial modes as widely as possible and a very narrowband Bragg reflector as one of the laser mirrors[14] and (2) the adoption of a travelling-wave resonator[15], which automatically encourages single axial-mode operation (by elimination of spatial hole burning). Selection of an appropriate mode is achieved with an FFP. An as yet unsolved problem is that of mode-hopping which occurs when the filter straddles two laser modes equally.

Single-frequency fibre lasers are efficient, stable, fibre-compatible components. They exhibit linewidths less than 10kHz with very low amplitude noise and an output power in excess of 50mW. These attributes together with a tunability over 40nm makes them very strong contenders for telecommunications WDM sources. Compared with DFB diode-lasers, they have narrower linewidth, lower noise and a higher output power. It remains to be seen whether these properties are sufficient to rival DFB diode-lasers as the preferred narrow-linewidth telecommunications source.

## Conclusions

Narrow-linewidth fibre filters with stop, pass or edge characteristics have been developed and add to the range of all-fibre components needed to construct fibre circuitry. Their applications in WDM networks, coherent communications and as noise filters for fibre amplifiers is becoming widespread. Tunable, single-frequency fibre lasers using narrowband fibre filters are also progressing rapidly and may in the future become commonplace as telecommunications light sources.

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