Waveguide-Type Optical Wavelength Filters

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Optical communications by dense wavelength division multiplexing (DWDM or WDM), which uses a number of wavelengths and a signal on each wavelength channel for transmission, has made massive progress as a high-speed, high-capacity optical communication system for the Internet age. A crucial device in this kind of communication system is the optical wavelength filter used to separate out the wavelengths. Many different methods are used to create optical wavelength filters[1]. We have been focussing our developments on optical waveguide technology, due to its excellent mass producibility and optical stability.

Optical wavelength filter applications

In WDM communications technology, firstly, it is necessary to have elements for separating respective wavelengths in order to discriminate between different signals carried on multiple wavelengths which are multiplexed in a single optical fibre. These elements may separate out the individual wavelengths to multiple output ports, or they may extract specific wavelengths only to a single port. The former type of element is known specially as a "wavelength demultiplexer" in the field of optical wavelength filters. The extracted optical wavelength may be fixed or tunable, and in the latter case, the element is known as a "tunable optical wavelength filter".

At the receiving end, these elements extract individual wavelengths, whilst at the sending end, they are used for the purpose of multiplexing a large number of wavelengths in a single optical fibre. A so-called "Optical Add / Drop Multiplexer" (OADM), on the other hand, extracts or introduces a specific wavelength channel at an intermediate stage of the transmission line, and is therefore used to build systems which have greater freedom in network design. In the future, there will be an increasing need for elements which can be tuned to extract different wavelengths, in order to provide a flexible response to traffic fluctuations or faults.

Another crucial application of optical wavelength filters is in the control and monitoring of the state of optical signals. A typical example of this is a filter used to equalize the gain for different wavelengths in an optical fibre amplifier. Moreover, wavelength monitors for observing wavelength fluctuation in a wavelength channel, or power fluctuation or noise at different wavelengths, are increasing in importance as wavelength intervals are narrowed to raise capacity in WDM communications. Besides this, various experiments have been conducted to study the use of wavelength filters in applications for compensating dispersion in the transmission line which is a cause of signal degradation. This article focuses on a device suitable for use as an optical wavelength monitor, which was developed jointly by Oki Electric's Optical Component Company, Corporate Research and Development Center, and Oki Electric Cable Co., Ltd.

Methods for optical wavelength monitoring

Essentially, an optical wavelength monitor can be based on one of two methods: one using a tunable optical wavelength filter, and the other using an element which functions as a wavelength demultiplexer for a fixed wavelength. Fig. 1 and Fig. 2 illustrate these two methods. Fig. 1 shows a method based on a tunable optical wavelength filter, whilst the scheme in Fig. 2 uses a wavelength demultiplexer.

In the method using a tunable optical wavelength filter, one wavelength channel is selected from the WDM signal by a filter element, and the wavelength and power of that signal are monitored. The device can be built using a relatively small number of photosensors, but this element must have a wavelength standard, as well as having very high wavelength resolution and being

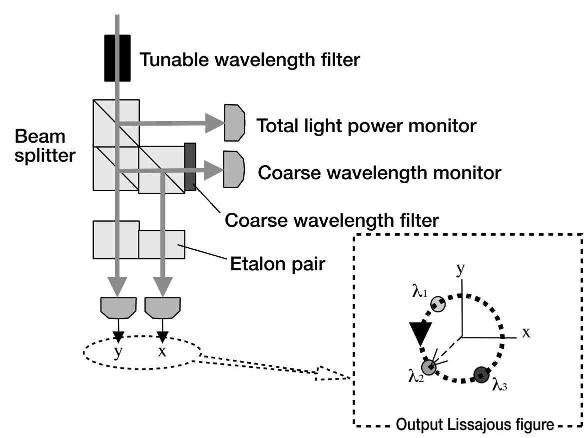

Fig. 1 Wavelength monitor using tunable wavelength filter

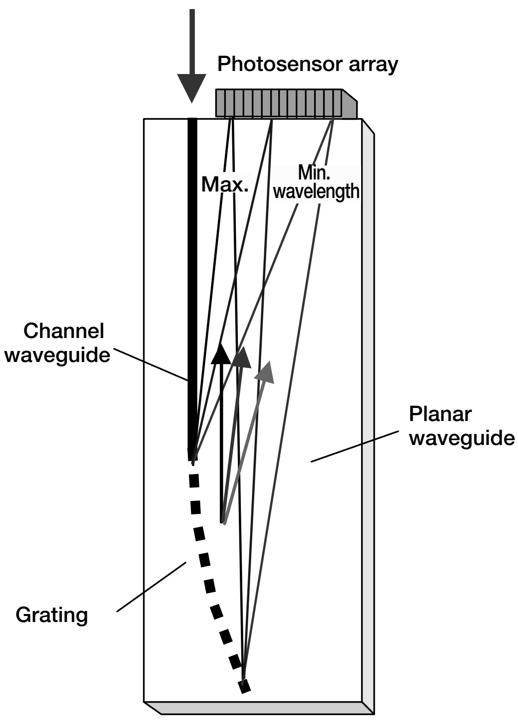

Fig. 2 Optical wavelength monitor using wavelength demultiplexer

tunable to a selected wavelength over a broad wavelength range, relatively quickly.

The wavelength standard may use a wavelength stabilizing light source, or an etalon (optical resonator) as illustrated in Fig. 1. An etalon is used in a laser diode module with stabilized wavelength, and has a periodical optical transmission output with respect to wavelength. In the illustrated method, two elaton outputs with a $^1/_4$ wavelength divergence in the optical transmission output cycle with respect to wavelength are signal processed to obtain a Lissajous figure for wavelength. The power can be derived from the angular direction in the Lissajous figure, and the wavelength and length of the radius vector. Moreover, an approximate value for the wavelength is measured by a thin-film filter (coarse wavelength filter in the diagram), and the light power is measured by light separated at a beam splitter. The array allocation may be constituted by multiple optical fibres in a single module.

On the other hand, in the wavelength demultiplexer method illustrated in Fig. 2, the optical signals in the light from a single optical fibre are first separated spatially according to wavelength, by means of a wavelength demultiplexer. The intensities of the optical signals at a focal plane are measured by an array of photosensors, to detect which wavelength components are present and in what amount. Since there is no tuning section, this system is advantageous in that the wavelength demultiplexer itself can be used as the wavelength standard. However, a drawback of this method is that a photosensor comprising a large number of photoreceptor elements must be used in order to improve the wavelength resolution, and hence the photosensor unit is very expensive. In general, a 512-element sensor is used for 50 GHz wavelength intervals and a 1024-element sensor is used for 25 GHz intervals.

Examples of tunable optical wavelength filters

In addition to their use in optical wavelength monitors, tunable optical wavelength filters are also extremely valuable elements in building OADM devices, for instance. A massive amount of research has been carried out in this field, but it remains very hard to come up with an element which combines features, such as high-resolution wavelength selection, with the ability to vary the wavelength at high speed and over a broad waveband. In the field of wavelength monitors and similar devices, interest is currently focused on designs which use micromachining techniques to move the mirror gap of a Fabry-Perot resonator mechanically. However, with this method, the mechanical motion of the mirror is an obstacle to achieving higher speed operation.

At Oki, on the other hand, we have achieved a tunable optical wavelength filter using an acousto-optical effect which has a microsecond-order tuning speed and a wavelength variation range of dozens of nanometers, and the company has carried out verification tests for a wavelength switching system.

There are also waveguide type elements based on the electro-optical effect, and the like, which combine an extremely fast tuning capability with excellent optical properties. Usually, the number of channels is determined by the magnitude of the electro-optical effect. Fig. 3 shows an example of a device developed

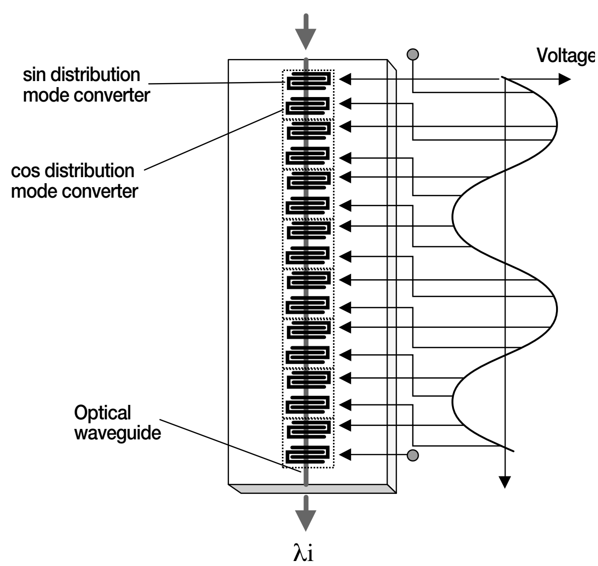

Fig. 3 Program-type tunable wavelength filter

by Oki, illustrating the method used to overcome this restriction and enable multiple channels to be selected simultaneously. A grating which causes mode conversion or reflection is divided into blocks, each block being divided into two parts, one generating a sin factor and the other a cos factor, in the form of a spatial grating strength distribution along the full length of the element. The sin grating is shifted by a 1/4 cycle position with respect to the cos grating. In this way, it is possible for any wavelength to be selected by the spatial grating strength distribution.

Wavelength demultiplexer using waveguide grating

The most well known type of wavelength demultiplexer using a waveguide is the arrayed waveguide grating (AWG) in which lens-shaped planar waveguides are joined by a waveguide array of different lengths.[2)] If the element is to be used in a wavelength monitor, it must have a resolution capable of extremely fine wavelength division, as well as having to cover the wide wavelength bandwidth, for instance, 40 nm, used in WDM communications. Moreover, in a photosensor element, in order to guarantee sensitivity and noise, there are limits on the degree to which the receptors can be reduced in size, and therefore it is necessary to focus a photoreceptor array which has a total width of some 1 – 2 cm. Since this has to be achieved in a small element, the photosensor and the wavelength splitting section cannot be spaced apart, and hence aberration is a problem. In the AWG element, a very high number of waveguide arrays are provided in order to satisfy these requirements, and the increased structural complexity and element size are disadvantageous in manufacturing terms. On the other hand, some devices use a grating in the planar waveguide. In this structure, light from an input waveguide is radiated into a planar waveguide, and is then diffracted by an array of reflector surfaces (grating) provided in the planar waveguide. The tip of an output waveguide is provided at the different focal position for each wavelength. By correctly adjusting the spacing of the reflector faces, the light is condensed without using a lens. This structure is simpler than an AWG, but due to problems of aberration, it is difficult to adapt to a relatively wide photosensor array.

At Oki, in our development of a device in this field, we have been concentrating on a structure which has a grating provided on a single waveguide and which is combined with a planar waveguide. The basic structure is that shown in Fig. 2, and comprises a planar waveguide on a substrate, which confines and propagates input light in a plane, and a channel waveguide located in the planar waveguide, which confines and propagates the light in both the vertical and horizontal directions, at a cross-sectional face. The light propagated by the channel waveguide is gradually reflected by the grating as it propagates from the channel waveguide into the planar waveguide. When the reflected light interferes at the photoreceptor array, then since the light phase varies with wavelength, the light will focus at different positions for each wavelength. The wavelength resolution of the element can be increased by forming the axis of the channel waveguide as vertically as possible with respect to the photoreceptor array. In a bulk element, this corresponds to installing a so-called "echelle grating", in which light is input to the grating at an angle close to the parallel.

Two types of grating can be used: one fabricated by altering the refractive index by ultraviolet light, such as a Fibre Bragg Grating (FBG), or one fabricated by micropatterning.

The UV light method can fabricate gratings of very small wavelength orders, and hence yields elements with good performance. Nevertheless, the material must be designed very carefully in order to achieve large changes in refractive index. By using a low-loss silica material as a waveguide and finely adjusting the fabrication conditions, we were able to achieve large refractive index change of the 10^{-3} order, without requiring the additional processes generally used, such as hydrogen implantation. What is more, by adopting a structure in which the channel waveguide is buried inside the planar waveguide, the element can be manufactured very easily by generating ultraviolet light sensitivity in the channel waveguide only. In actual fabrication, an optical phase mask comprising grating grooves is placed on top of a silica substrate sample and irradiated with ultraviolet light. Due to diffraction effects, an interference pattern of the UV light can be generated, and this interference pattern in turn forms a grating pattern in the sample in which the refractive index changes periodically.

A grating fabricated by micropatterning uses a method which forms reflection planes in the shape of the channel waveguide. An optical waveguide is created in the form of a dotted line, and the gap interfaces in the dotted-line-shaped waveguide are used as a grating. This method is highly advantageous in that the grating can be fabricated simultaneously with the channel waveguide, thereby simplifying the fabrication process. In order to reduce the difficulty of the micropatterning process, desirably, the grating is formed with relatively large intervals. Furthermore, in order to lower the accuracy required in fabricating the intervals, a grating is formed by creating reflection planes which have different angles at either end of the interval in the dotted-line waveguide structure. Since the wavelength peaks of these two reflection planes are formed in different points at different wavelengths, the fabrication accuracy can be eased whilst still achieving a design which avoids mutual interference between the wavelengths. Furthermore, by using vertical reflection planes for the one-sided reflection planes and adopting a two-level structure, it is also possible to diminish the reflectivity at these planes.

The shape of the channel waveguide and the pitch between the reflection planes of the grating are based on a special new design which focuses the light without

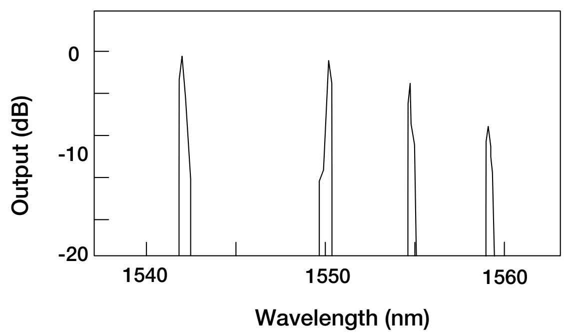

Fig. 4 Example of wavelength demultiplexer output (wavelengths at output positions 2 mm apart)

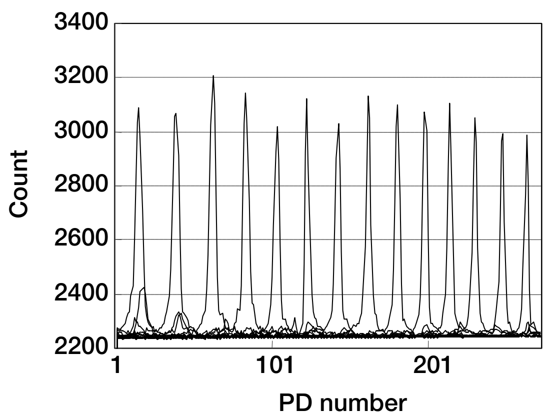

Fig. 5 Example of output from PD array (1 nm intervals from wavelength of 1546 nm)

using a lens. In order to prevent aberration over the relatively broad range of the photosensor array, a plurality of optimum focusing positions are provided. In this way, the light is focused over a broad range of wavelengths, without the use of a lens.

Fig. 4 shows the main output peaks in one set of characteristics obtained for a UV grating. Secondary peaks caused by higher-order modes can also be seen, depending on the fabrication conditions and incident position. The dimensions of the fabricated element match the 1.5 cm width of the photosensor array, and it has a length of 6 cm. The spatial dispersion, in other words, the change in the position of the light spot with variation in wavelength, provides a measure for comparing the wavelength resolution, and here a maximum spatial dispersion value of 7.5 x 10^5 was obtained. This figure is about one order superior to that of generic devices. With a grating length of approximately 5 mm, it was possible to split light separated by 0.2 nm intervals and having a spot size maximum diameter of around 40 microns. By careful adjustment of the processing conditions, polarization dependence was reduced to 0.1 nm or less, and a value of around 25 dB was obtained for the extinction ratio. The designed operational wavelength range was set to 35 nm, but a wavelength range of 45 nm could be achieved by increasing the element size by several mm. When the grating was formed into a combined module with a photosensor array, it was possible to split light from a –30 dBm tunable wavelength light source, at approximately 15 image pixels per 1 nm wavelength, and an output signal of 3V was obtained. Fig. 5 shows an example of results for the dotted line-shaped optical waveguide element. The module was 3 cm wide and approximately 8 cm long.

An element used in a wavelength monitor is required to have more rigorous wavelength characteristics than a wavelength demultiplexer used for communication. However, through application of the technology described above, we also expect to achieve high performance in communications elements as well.

Conclusion

This essay has looked at the applications of optical wavelength filters, and introduced the waveguide type elements we have developed so far. We see both tunable optical wavelength filters and wavelength demultiplexers becoming increasingly important in WDM optical communications systems from here on, as wavelengths are divided ever more finely. At Oki, we will also be carrying out active and painstaking developments relating to these other types of optical wavelength filters, in order to help build the systems of the future. ◆◆

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