# Development of a Crystal-Type Optical Interleaving Filter

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**ABSTRACT** In recent years wavelength-division multiplexing (WDM) technology has been adopted in configuring large-capacity long-haul fiber-optic communications networks, and bandwidths are becoming narrower in an effort to obtain higher densities on communication wavelengths. This has led to a need for interleaving filters, which from a single input can demultiplex alternate wavelengths to separate outputs. By developing a proprietary configuration, the authors have succeeded in developing an optical interleaving filter that does not require temperature control. This paper describes the configuration of the module, and reports on the properties of prototypes that were fabricated.

## 1. INTRODUCTION

Since the beginning of the 1990s Internet use has spread to all corners of the world, creating a massive increase in the volume of communications traffic. In fiber-optic transmission systems, there have been major advances in WDM technology, resulting in wide use of this method, which uses wavelength-division multiplexing to place multiple signals of different wavelengths on a single fiber. Internet bandwidths have increased in recent years, but with an on-going need for high-speed transmission of large volumes of data for still and moving images there is every indication that there will be further leaps in communication traffic. To cope with this trend a technology is being introduced which increases wavelength density and uses a larger number of channels. It is known as dense WDM.

In DWDM systems narrow-band signals of from 50 GHz to 25 GHz frequency spacing must be multiplexed with high accuracy and then demultiplexed into the component signal wavelengths. This is done by devices known as MUX/DEMUX modules using AWGs and filters, but with these modules it is becoming extremely difficult technologically to increase densities above 50 GHz. Thus there is a need for modules capable of taking signals multiplexed to some extent by a MUX module and lumping them together to achieve greater densities, and of demultiplexing dense signals at broad frequency spacing.

Methods of realizing modules having these functions include those using crystals and those using optical fibers, but those using fibers suffer from a number of disadvantages: their characteristics are heavily temperature-dependent and since the fibers need to be accommodated to the designed routing, they are more bulky.

This paper reports on the development of a crystal-type optical interleaving filter that can multiplex two signals at 100-GHz spacing to a spacing of 50 GHz, and demultiplex the signal with 50-GHz spacing to a spacing of 100-GHz.

## 2. BASIC CONFIGURATION

Figure 1 shows the basic configuration.

On one side of the light path determining section containing optical elements such as a birefringent crystal and Faraday rotator and the wavelength multiplexing/demultiplexing (MUX/DEMUX) section comprising an interference filter, there are disposed three ports. In each port an aspherical lens is disposed at the end of a single-mode fiber (SMF), so that the divergent light from the end of the fiber is collimated by the lens forming a connection between the ports. The optical fiber and lens are fixed in place by YAG welding and no adhesive is used in the light path for reasons of power resistance.

The light path determining section is of a non-reciprocal structure, having an isolation function that prevents propa-

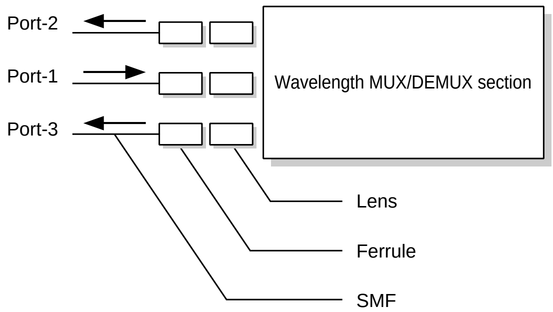


**Figure 1 Basic configuration of crystal-type optical interleaving filter.**

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gation of light in the reverse direction. By being selective in the structure of the optical elements used in the light path determining section it is possible for them to be used in either a multiplexing or demultiplexing module.

As an example, we will describe the propagation of light during demultiplexing.

When the wavelength multiplexed signal injected at Port 1 enters the wavelength MUX/DEMUX section it is separated by the interference filter to odd and even wavelengths that are both at the same frequency spacing. With this the two parts of the divided signal are mutually cross-polarized, their optical paths are converted by the light path determining section, and they are output to Port 2 and Port 3 respectively.

In wavelength multiplexing, when signals from Port 2 and Port 3, each having the same frequency spacing and a wavelength shifted by one-half frequency spacing the respective signals are multiplexed and a further multiplexed signal with a frequency spacing one-half that of the injected signal is output from Port 1.

Since the interference filter has ordinary temperature characteristics, the peak wavelength of optical signals multiplexed or demultiplexed by the crystal-type interleaving filter will vary with temperature. In the interleaving filter described in this work, optical design is applied to compensate for the temperature dependence of the interference filter so that the module as a whole is of athermal construction, with diminished temperature dependence of the peak center wavelength. Since temperature control is not required, it is easier to handle and more cost-effective, and the space that the temperature regulating circuitry would have occupied is saved. This has made it possible to design a module only 1/15 the volume of one with temperature regulation. The external appearance of the interleaving filter module is shown in Figure 2. Its dimensions are 60 x 20 x 8.5 mm.

## 3. TYPICAL APPLICATIONS

Figure 3 shows an application of 100-GHz/50-GHz crystal-type optical interleaving filters in a DWDM system. By means of an AWG or other multiplexing module signals multiplexed at 100-GHz frequency spacing are injected into Port 2 and Port 3 of the crystal-type interleaving filter with wavelength multiplexing function. The wavelengths of the signals so injected at Ports 2 and 3 are each shifted by one-half of the frequency spacing, or 50 GHz. These signals are then lump multiplexed by the crystal-type interleaving filter into signals with a frequency spacing of 50 GHz. If the multiplexed signal is injected into Port 1 of a crystal-type interleaving filter having a wavelength demultiplexing function, a signal with 50-GHz spacing can be demultiplexed into two signals with 100-GHz spacing.

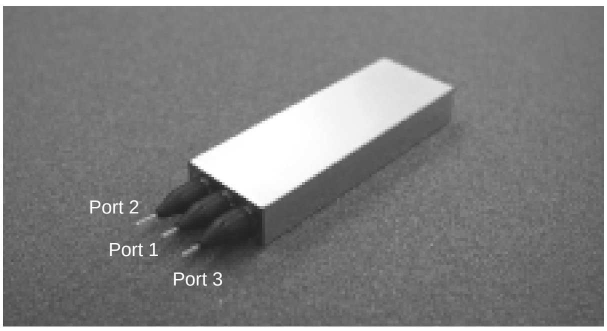



**Figure 2 External appearance of crystal-type optical interleaving filter.**

## 4. TARGET SPECIFICATIONS

With a view to achieving broad band and low insertion loss, together with sufficient bandwidth and channel isolation for high-density transmission, the target specifications shown in Table 1 were adopted.

## 5. PERFORMANCE CHARACTERISTICS

### 5.1 Transmission Waveform

The transmission waveform of the crystal-type interleaving filter is shown in Figure 4, and expansions of the waveform are shown in Figure 5(a) and 5(b) for the shorter and longer wavelengths respectively. In the 1525-1565-nm range, the transmission spectra of Ports 2 and 3 show a cyclic spectrum with 100-GHz spacing. It can also be confirmed that the peak center wavelength between the two ports show an alternately shifted transmission characteristic.

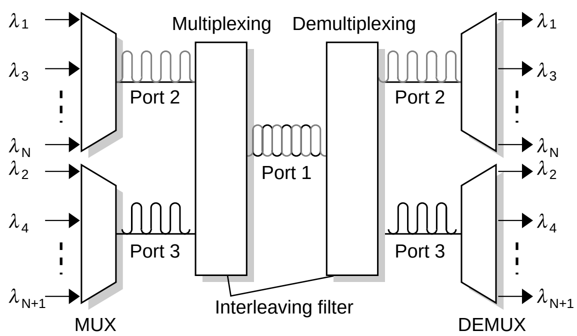



**Figure 3 Application of crystal-type optical interleaving filters in DWDM system.**

**Table 1 Target specifications of optical interleaving filter.**

| Item | Specification | |
|---|---|---|
| Insertion loss | @±10 GHz | <1.5 dB |
| PDL | @±10 GHz | <0.4 dB |
| Transmission bandwidth | @-0.5 dB | ±10 GHz |
| Rejection bandwidth | @-17 dB | ±5 GHz |
| Isolation | | >45 dB |
| Operating wavelength range $\lambda_{op}$ | 1525~1565 nm | |
| Operating temperature range $T_{op}$ | 0~65°C | |

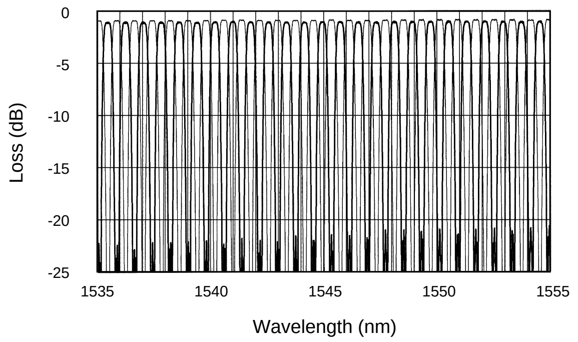
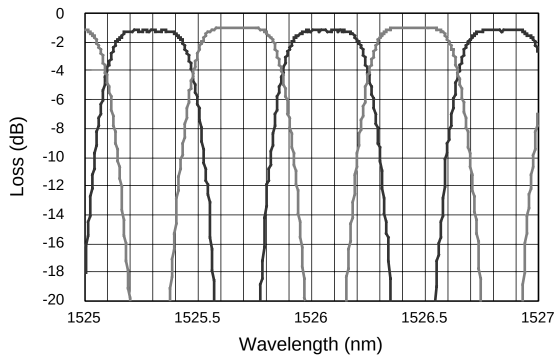
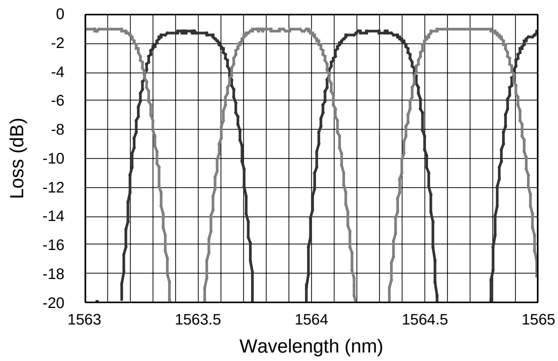



**Figure 4 Transmission waveform of selected interleaving filter.**




a)1525-1527 nm




b)1563-1565 nm

**Figure 5 Expansion of selected transmission waveforms.**

Figure 6 shows the results of measurements of the temperature dependence of the transmission waveform of the interleaving filter, together with a mask that shows transmission bandwidth and rejection bandwidth from Table 1. The measurement temperatures ranged from 5 to 50°C, and the range of temperature dependence of the peak center wavelength was ±1 pm/°C or less. From this graph we can see that both the transmission and rejection bandwidths are substantially within the standard masks. The range of temperatures was ±5°C narrower than the target, but it was possible to confirm the reduction in temperature dependence.

## 5.2 Insertion Loss Distribution

Figures 7 and 8 give histograms showing the distribution of insertion loss for multiplexer-type and demultiplexer-type interleaving filters. An insertion loss of 1 dB or less was achieved by more than 80% of the modules from Port 2 to Port 1 in the multiplexing type, and by more 100% of the modules from Port 3 to Port 1 in the multiplexing type, as well as in the demultiplexing type.

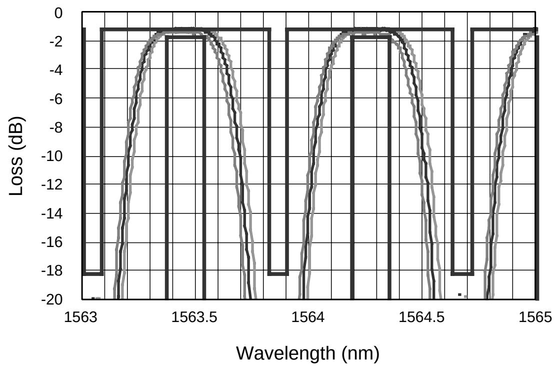



**Figure 6 Temperature dependence of transmission waveform.**

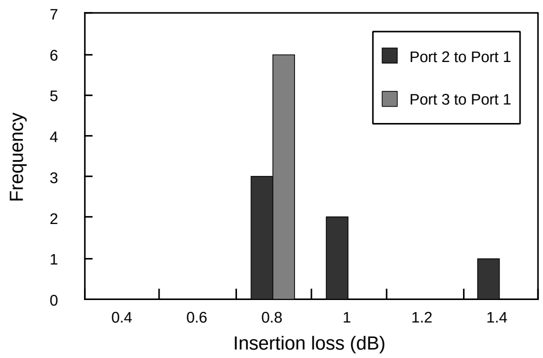



**Figure 7 Histogram of insertion loss of MUX-type interleaving filter.**

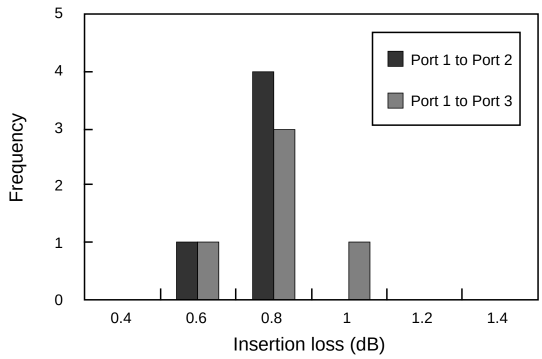



**Figure 8 Histogram of insertion loss of DEMUX-type interleaving filter.**

## 5.3 Polarization-Dependent Loss (PDL)

Figure 9 gives a histogram showing the distribution of polarization dependent loss at room temperature. About 80% of modules shows a superior PDL characteristic of 0.04 dB or less.

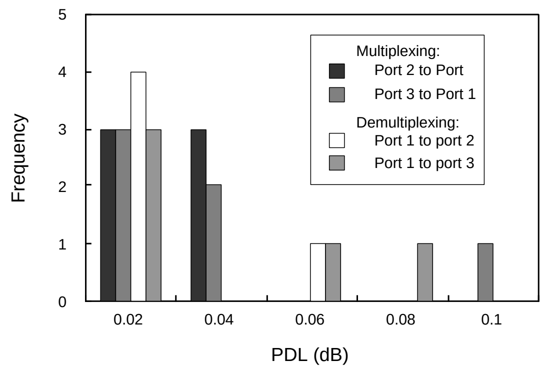



**Figure 9 Histogram of polarization dependent loss of interleaving filter.**

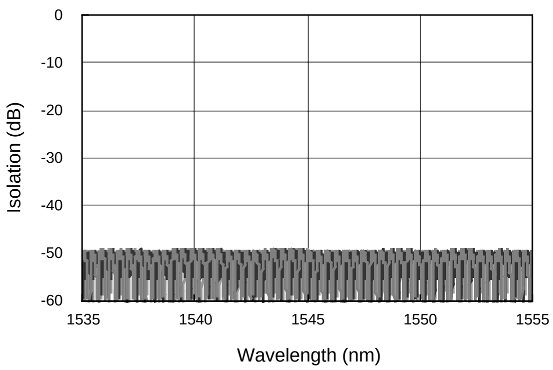



**Figure 10 Isolation of MUX-type interleaving filter, Port 1 to Port 2.**

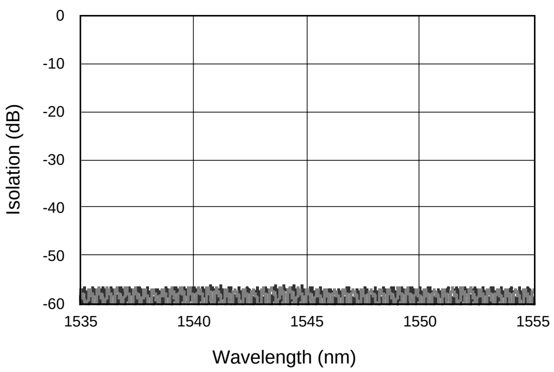



**Figure 11 Isolation of MUX-type interleaving filter, Port 1 to Port 3.**

### 5.4 Isolation

The relationship between isolation and wavelength is shown for a multiplexing interleaving filter in Figure 10 from Port 1 to Port 2, and in Figure 11 from Port 1 to Port 3. For all ports a high degree of isolation was achieved--45 dB or better at 1525-1565 nm, enough to satisfy operating requirements. The demultiplexing type also showed isolation of 45 dB or better in the operating wavelength range.

## 6. CONCLUSION

A compact 50-GHz optical interleaving filter featuring low insertion loss has been developed. It is of the athermal type, which is recently in demand, and the temperature dependence of peak center wavelength was held to 1 pm/°C, and it thus promises to make a significant contribution to improving the performance of dense wavelength-division multiplexing (DWDM) systems. The next task is to confirm reliability and to effect further improvements in the temperature dependence characteristic of the peak center wavelength. It is also proposed to develop optical interleaving filters using the same technology for the next generation of narrower-band (25 GHz) systems.