

# Integrated holographic filters for flat-passband optical multiplexers

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**Abstract:** The first fully-integrated (26x4x1 mm, silica-on-silicon), single-mode, CWDM multiplexer matching performance of bulk-optical alternatives is described as are the enabling, lithographically-scribed, integrated holographic filters, which uniquely provide flat passbands without loss penalty.

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## 1. Introduction

Multiplexing is crucial to all WDM applications and it is imperative to identify optimal means of providing such function. Existing multiplexing means center on integrated grating-based solutions, on the one hand, and discrete thin-film filter solutions, on the other. Each of these multiplexing approaches has strengths and weaknesses. In terms of strengths, the integrated means provides for robust and simple devices, while the thin-film filter solutions offer very powerful and flexible passband control and tailoring. On the weakness side, existing integrated solutions suffer a fundamental linkage between increased insertion loss (IL) and passband flattening (especially in single-mode systems), while thin-film multiplexers require myriad precision-aligned optical elements. We describe here a new multiplexing approach that combines the strengths of grating-based integrated solutions (like AWGs) with the strengths of thin-film filter solutions. Finally, one can simultaneously enjoy the advantages of monolithic integration while preserving the passband flexibility normally reserved to thin-film devices. The integrated holographic devices described here are applicable to any WDM standard, and are enabled by planar waveguide technology and the high resolution patterning newly available through advances in Deep Ultraviolet (DUV) photolithography. To demonstrate the new approach to integrated filtering, which may be realized in various material formats and combined with other device functionalities, we have designed and fabricated a high performance, single-mode, integrated Coarse WDM multiplexer – a function very difficult to realize with prior integrated filtering technologies. Performance realized is competitive with traditional thin-film CWDM devices.

Integrated spectral filters in widespread use are based primarily on reflective or transmissive gratings, e. g. arrayed waveguide gratings [1-3], echelle gratings [4-5], etc. These gratings function on the basis of angular dispersion. Angularly dispersive devices are very good at routing many signal channels with Gaussian-like passbands into separate output channels. But they have a fundamental limitation when it comes to mapping channels of complex passband (spanning a range of output directions) into single-mode (direction specific) outputs. Generally speaking, angularly dispersive filters can be configured to deliver tailored, e. g. flat top, passbands into single-mode outputs, but to do so requires an insertion loss (IL) penalty, which becomes more severe as the number of grating resolution bandwidths coupled to the output increases. [6-7] It has been shown that one can use double grating devices interconnected with waveguide arrays to more flexibly route tailored passbands into single-mode outputs. [8-9] In such cases, the second grating is employed to realign selected angularly dispersed signals into a common output direction. While adding a second grating provides substantially more passband flexibility, its addition carries with it the price of increased complexity and size.

Angular dispersion is not the only spectral filtering mechanism available. Thin film filters operate by a different principle, i. e. multipath interference. Passbands are defined through the interaction of unidirectional light with a series of dielectric interfaces. Quite general passbands can be achieved and routed to single-mode outputs without fundamental IL penalty. Thin-film filters combine device simplicity and compactness with single-mode function, but are not compatible with monolithic integration in their normal form.

Integrated holographic filtering devices are 2D volume gratings. They function via multipath interference, like thin-film filters, and thus offer flexible passband control without IL penalty. Functionally, integrated holographic devices may, in fact, be thought of as integrated thin-film filters. The reflective interfaces of the integrated

holographic filter, lithographically etched trenches, are curved so that they provide focusing of signals between input and output ports as well as providing arbitrary passband tailoring. [10,11] It is only with the advent of modern DUV photolithographic patterning tools with resolution below 0.25 micron that volume grating filters can be flexibly apodized and manufactured [12]

## 2. Device Description

Fig. 1 gives a schematic view of a four-channel multiplexer based on integrated holographic filters. The top portion of the figure looks down on a silica-on-silicon die.

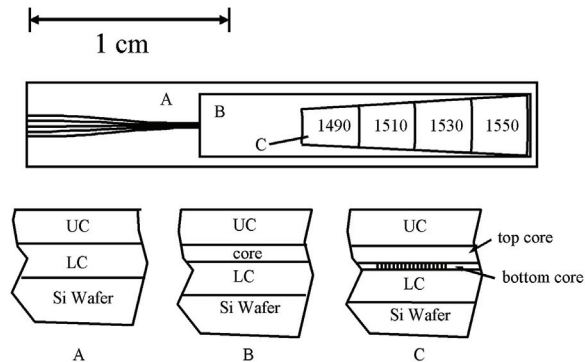


Fig. 1. Schematic top view of four-channel multiplexer chip with cross-section views of chip regions A, B and C.

The regions labeled A, B, and C have the respective cross sections shown at the bottom of the figure. The lines on the left of the die view (top) represent channel waveguides coupling signals from the edge of the die to the slab waveguide regions B and C. Region A is non-guiding. The overall die dimensions are approximately 4 x 26 mm. The central channel waveguide is common and in a demultiplexing implementation each of the four filters focuses signals emerging from the common channel and within its respective reflection passband to one of the outlying four channels. The focusing action is reciprocal enabling multiplexing and demultiplexing function. In the cross-sectional views, the upper (UC) and lower (LC) cladding layers are, respectively, doped silica and thermal oxide. Both cladding layers have a thickness of  $\approx 14$  microns and a refractive index  $\approx 1.45$ . The core region comprises a single (two) layer(s) and is approximately 2.3 (2.6) microns thick in region B (C). The upper (lower) core layer has a refractive index about 0.7 (3) percent above the cladding index. In all regions, only a single vertical spatial mode is supported. The filter structure is etched into the top of the lower core layer in region C using Deep Ultraviolet (DUV) reduction photolithography. The diffractive contours comprising the volume holographic grating individually image a portion of the input signal to the output channel. In the present instance unity-conjugate ratio imaging is employed, but the contours can be configured to provide optimal wavefront matching between ports of essentially arbitrary nature. There are about 5400 diffractive contours in each  $\approx 2.7$ -mm-long filter section. The higher index core layer serves the important function of shifting the signal mode to better overlap the etched diffractive contours and therefore increase reflective coupling.

The integrated holographic filters fabricated are designed to meet the passband requirements of coarse wavelength-division multiplexing (CWDM), i.e. 13-nm wide, flat-top passbands with low IL. Such passbands are difficult to achieve at acceptable IL levels with current single-mode compatible, integrated filters. [8,9] To achieve such a wide passband, the average spacing of diffractive contours within a filter is chirped. To achieve rapid passband falloff in the wings, the reflective amplitude of the filter is apodized using a correlated-line apodization scheme. [13] As described elsewhere, [13] correlated-line apodization provides for reflective amplitude control by spatial placement of small sets of diffractive contours so as to interferometrically set the net reflectivity of the set to desired values. This method allows one to use standard binary (single depth) contour etching.

## 3. Measurements

The measured reflection spectrum of each of the four integrated filters is shown in Fig. 2. The IL ranges from 1.6 to 2.2 dB and includes a 1.3 dB fiber-to-die coupling loss. On-chip loss of the first channel (about 1.6 dB IL) is thus only about 0.3 dB. It is believed that on-chip loss comes primarily from defocusing effects introduced by avoidable film inhomogeneities

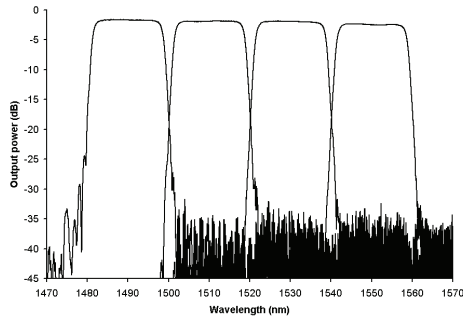


Fig. 2. Reflection passbands for each of the four apodized multiplexer/demultiplexer channels

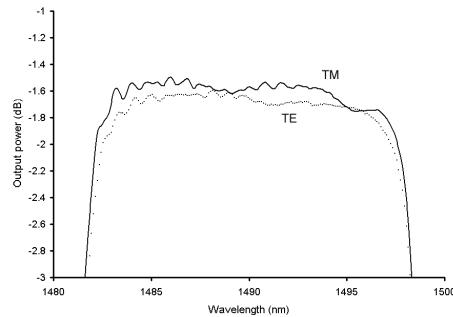


Fig. 3. An apodized filter passband shown on an expanded scale explicitly showing polarization dependence.

The passband flatness is found to be better than 0.3 dB. Isolation between adjacent channels is better than 34 dB. Channel-cross talk may be further reduced by increasing the  $\approx 50$  micron spacing of output channel waveguides.

The polarization dependent loss is less than 0.2 dB for all four channels (see Fig. 3). The filters are found to shift with temperature at a rate of  $\approx 10$  pm/C. The passbands of Fig. 2 exceed the 13-nm CWDM standard and the excess widths serve as guardbands sufficiently wide to make the device passively athermal over approximately 100 C.

To produce the steep falloff at the passband edges shown in Figs. 2 and 3, apodization was necessary. For comparison, a multiplexer comprised of unapodized integrated holographic filters was constructed. The fall-off is substantially slower – as will be detailed in the presentation.

#### 4. Summary

Monolithically integrated, single-mode-compatible multiplexers, based on integrated holographic filters and providing uniquely wide, flat, and low-IL passbands, have been demonstrated and found to be superior to all existing integrated and competitive with existing thin-film-filter-based alternatives. The integrated holographic mux functions via the same principle as thin-film filters but does so in a fully integrated rather than discrete environment and incorporates signal routing function as well. Lithographically scribed, integrated holographic filtering elements may provide an important building-block element of future photonic integration providing unique low-IL passband control and pathways to very low cost stamped and molded components as well for access and datacentric applications.

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