Invited Paper

Submicron planar waveguide diffractive photonics

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ABSTRACT

Recent advances in semiconductor fabrication tools, which now support 100-nm pixilation and centimeter-scale spatial coherence, create intriguing new opportunities in integrated photonics. Application of the latest generation of fabrication tools allows for the implementation of broad new photonic device function based on 2D distributed diffractive structures such as holographic Bragg reflectors (HBRs) – devices that provide generalized spatial routing of signals within a planar waveguide circuit (e. g. silica-on-silicon) while at the same time providing powerful spectral filtering function. HBRs and other 2D distributed diffractive devices promise to open disruptive pathways to integrated photonic solutions characterized by high performance, small footprint, and extremely low cost especially when fabricated via stamping/nanoimprinting

Keywords: Grating, waveguide, integrated, planar, holographic Bragg reflector, distributed diffractive device, photolithography, etch, silica-on-silicon, stamping, nanoimprinting, integrated photonics, slab waveguide, spectral filter, integrated spectrometer, spectral comparator, waveform comparator, hologram, integrated holographics, volume hologram, correlator.

1. INTRODUCTION

The interaction of light with dielectric media tailored with intricate spatial structure is an intriguing subject. Increased understanding of phenomenology associated with such interactions may open the door to photonic device function far beyond that offered by today's photonic integrated circuits, which are based primarily on simple channel and slab waveguide structures. We focus here on planar waveguide media patterned at the sub-wavelength scale to provide various device functions.

1.1. Photonic Crystals

In general context of nano-crafted dielectric media, photonic crystal or photonic bandgap type structures have attracted considerable recent attention. Such structures are implemented in two- or three-dimensions, generally have translational invariance characteristic of molecular matter, and like their molecular analogs suppress or otherwise control broad ranges of modes (electronic in the molecular case, photonic here) so as to open gaps in the spectrum of allowed traveling-wave modes. In order to achieve control over photonic modes of disparate orientations, it is found necessary to introduce structures whose refractive index contrast is quite large and typically exhibit a seriously high level of loss from incoherent defect-related scattering. Photonic bandgap materials have been proposed for a variety of integrated photonic applications, for example, as a means of guiding signals. The photonic bandgap approach to signal control may be loosely described as the suppression of all possible propagation options except one – the one consistent with circuit function. As blocking all unwanted photonic modes requires effort, overall signal control via the photonic bandgap approach places high constraints of device design, composition, and fabrication.

1.2. Integrated holographics

There is another less-well-known class of nano-structured dielectric media eminently useful in the fabrication of photonic devices. This class contains entirely different types of structure, i. e. integrated holographic structure. In many respects, integrated holographic structures are opposite to those employed to create photonic bandgap materials. In integrated holographics, structures are crafted to control the particular photonic signal mode(s) of concern in an integrated device while leaving non-signal modes alone. Integrated holographic devices act to route and process target

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modes rather than by blocking and suppressing all non-target modes. In exchange for giving up control of all extraneous modes, one can work with a much broader range of structural geometries and refractive index contrasts. An integrated holographic device may be designed with high index contrast materials to provide mode confinement equal to that provided by photonic bandgap materials. Alternatively, an integrated holographic device may be designed with very low refractive index contrast, hence very low scattering loss and low sensitivity to most forms of fabrication defects. The flexibility to employ broad ranges of refractive index contrast and geometry is a defining feature of integrated holographic devices. Flexible design follows from signal-mode-specific control structures. In the limit of low refractive index contrast, integrated holographic structures become spatially extended and highly wavelength and wavefront selective. In fact, the detailed nature of spectral and spatial selectivity can be precisely controlled providing spectral filtering function for selected modes.

1.3. Fabrication

Key to the utility of any design concept is the ability to actually fabricate final devices in a robust, cost-effective format. Integrated holographic design comprises computer-based structure calculation based on volume holographic concepts, generation of a structure data file in a standard format like gds2, laser-writing the structure to a mask, and patterning the structure on a wafer by, for example, reduction photolithography followed by binary etch. Typical feature size in integrated holographic structures is on the order of one-quarter of the in-waveguide signal wavelength, which in the case of silica guides is 250 nm while for semiconductor (Si, InP, etc.) guides is 120 nm when dealing with 1.5 micron (vacuum) wavelength signals. As the feature size for integrated holographic structures is quite small, only recent advancements in photolithographic resolution along with absolute positioning accuracy over centimeter-scale fields, have made their application practical. Typically, integrated holographic patterns comprise curvilinear contours etched into one of the faces of a slab waveguide core (or into an internal interface between multiple core sublayers). Significantly, such patterns may be created in pliable waveguide materials (polymers) via methods of nanoimprinting/stamping/molding using, for example, a photolithographically patterned master. Integrated holographic devices made by such means may be important in reducing overall costs of photonic integration especially in cases where performance is secondary to cost. In the case of low refractive index contrast (a few percent), integrated holographic devices may span hundreds of microns to a few millimeters in size, and small, pointlike, imperfections in the fabricated structure do not significantly degrade device performance. As a result, integrated holographic devices lend themselves to high yield and high reliability.

2. INTEGRATED HOLOGRAPHIC DEVICES

2.1. Holographic Bragg reflector (HBR)

Holographic Bragg reflectors (HBRs) are volume holographic structures[1] typically implemented in slab waveguides. An HBR comprises a family of diffractive contours, each of which provides an optimized spatial wavefront transformation (e. g. focusing an input signal beam to an output port). Signal beams interact with many diffractive contours in succession as they propagate within the planar waveguide. Contours are typically aspherics similar to those that might be employed in optimized free-space aspheric imaging elements and can be viewed (and calculated) as interference fringes between the desired input and output signal beams. Contours are typically spaced by half an in-guide wavelength of the signal beam for first-order devices or a multiple of this spacing for higher orders. Collective interference of diffracted wavefronts from the family of diffractive contours provides spectral selectivity and hence filtering, whose bandpass function can be controlled in great detail by design of the reflective amplitude and relative phase of the various contours. Methods of introducing both amplitude and phase control of diffractive contours can be employed[2,3] that are entirely consistent with reliable and lithographically friendly binary etch processes. Owing to the precise lithographic fabrication approach utilized, HBRs offer spectral filtering function that is more controllable than available in fiber Bragg gratings. The 2D HBR structures have separate input and output paths as well, providing for convenient circulator-free filtering performance. With modest refractive index contrast between diffractive contour fill and core waveguide materials (e. g. 1-5%), HBR devices can support very large overall reflective bandwidths - passbands as wide as hundreds of nanometers are easily available. Owing to the high spatial coherence (1-2 cm) available using state of the art waveguide and patterning tools, HBR spectral resolution as fine as 5-10 GHz is achievable. Wide reflective bandwidth and high resolution provide the ability to support very complex and detailed

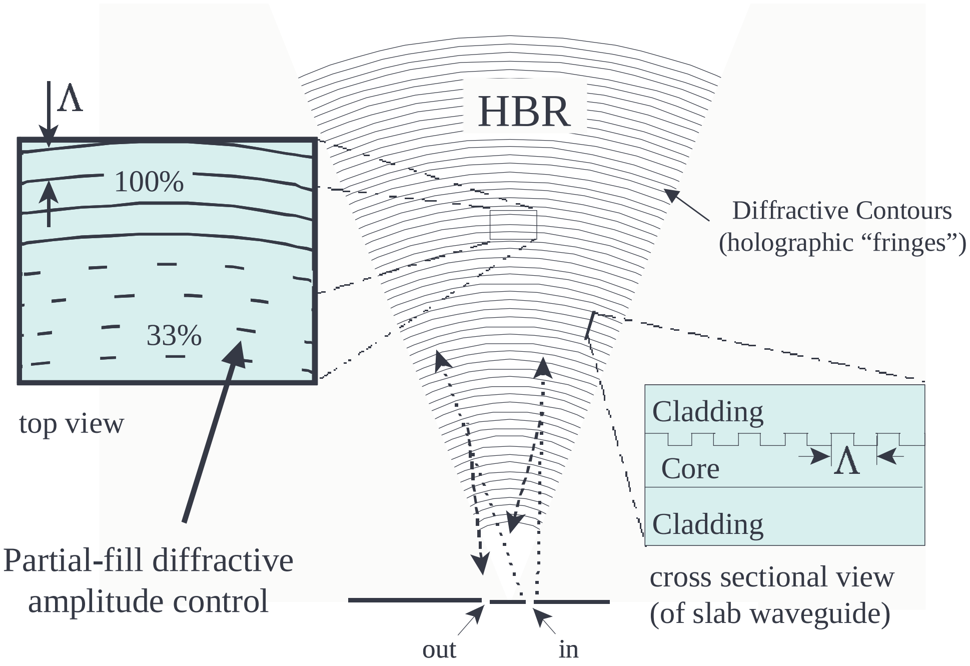

Figure 1. Simple near retro-reflective Holographic Bragg Reflector (HBR).

reflection spectra even matching complex molecular spectra. HBR devices provide the best features of fiber-grating filters and thin-film filters in a single integrated format while at the same time providing signal routing within the integrated photonic circuit. As powerful spectral filtering devices, HBRs can be employed in a multitude of applications including: simple bandpass filtering, signal coding/decoding for use, for example, in optical code-division multiplexing applications, real-time temporal waveform correlation as might be required in optical packet recognition, spectral signature recognition, etc.

Methods of overlaying multiple distributed Bragg reflectors provide for the integration of many separate routing/filtering functions on each chip. Combination of multiple integrated holographic structures with intervening free propagation within the slab waveguide allows for powerful mode transformation function. A single integrated holographic structure allows for quite arbitrary local wavefront phase transformation. Two or more successive integrated holographic structures provide generally for both wavefront phase and power transformations.

2.1.1. Simple retro-reflective HBR spectral filter

Figure 1 shows a simple HBR focusing spectral filter set up for near retro-reflection[4]. The diffractive contours can be calculated as general aspherics or approximated as simple geometric circular or elliptical curves – with the conic sections producing well-known aberrations. Fractional writing (insert at left of Figure 1) of nominally continuous contours provides one approach to controlling the reflective amplitude of individual contours and is compatible with lithographically friendly binary etch. Analysis[2] reveals that fractional writing of contours does not significantly degrade imaging properties especially when written portions are appropriately spaced and correlated from contour-to-contour. Changes in the effective waveguide refractive index introduced by changes in the fraction of the diffractive contours written must be accounted for when the partial writing approach is used to provide amplitude apodization for tailored spectral filtering. Alternatively, another method of diffractive amplitude control referred to as correlated-line-set apodization may be employed[3]. In the correlated-line-set approach to amplitude control, all diffractive contours are equally written, but the contours within a set are symmetrically displaced so as to interferometrically vary the net reflection amplitude of the set. Amplitude control exercised by correlated displacement does not introduce significant coupling between diffractive amplitude and effective waveguide refractive index. The relative phase of a diffractive contour (or a set of contours) can be controlled by spatial translation about its nominal location with displacements of ±λ/4n leading to ±π phase changes, where n is the effective waveguide refractive index and λ is the vacuum signal wavelength.

The individual diffractive contours in a simple retro-reflective HBR create output wavefronts optimally matched to the mode of the output port, which may simply be the edge of the chip as shown in Figure 1 or comprise a channel waveguide leading elsewhere on or off chip. Alternatively, the diffractive contours may collimate or otherwise route the output for interaction with subsequent HBR devices. The cross sectional view at lower right of Figure 1 shows the core and bilateral cladding layers of the HBR slab waveguide. Diffractive contours are etched into the interface between the upper cladding and waveguide core. More advanced internal waveguide designs involve two-or-more core waveguide layers with diffractive contours etched into interfaces between core sublayers. Addition of multiple core sublayers has the advantage of allowing concentration of the guided mode into the region containing diffractive contour interfaces thereby enhancing HBR-modal coupling.

In the absence of significant multiple scattering (at low reflectivity), the reflection spectrum of the HBR shown in Figure 1 is proportional to the Fourier transform of the HBR's complex reflective amplitude expressed as a function of round trip optical depth. In the presence of multiple scattering more complex algorithms must be employed to design the HBR reflection spectrum, but generally these methods are entirely analogous to those developed for the calculation of fiber Bragg grating spectra. In cases where diffractive contours are approximated by simple geometric curves and do not produce identical wavefronts at the output port, fiber Bragg grating calculations will have to be generalized to account for this fact.

2.1.2. Multiple HBR devices

An array of independent nearly retro-reflective HBR structures may be fabricated in stacked, interleaved, or superimposed form so as to provide a number of functions including multiplexing. The geometries just mentioned are depicted in Figure 2. The optimal approach to implementing a multi-HBR device depends on the specifics of the intended application. General approaches are identified here.

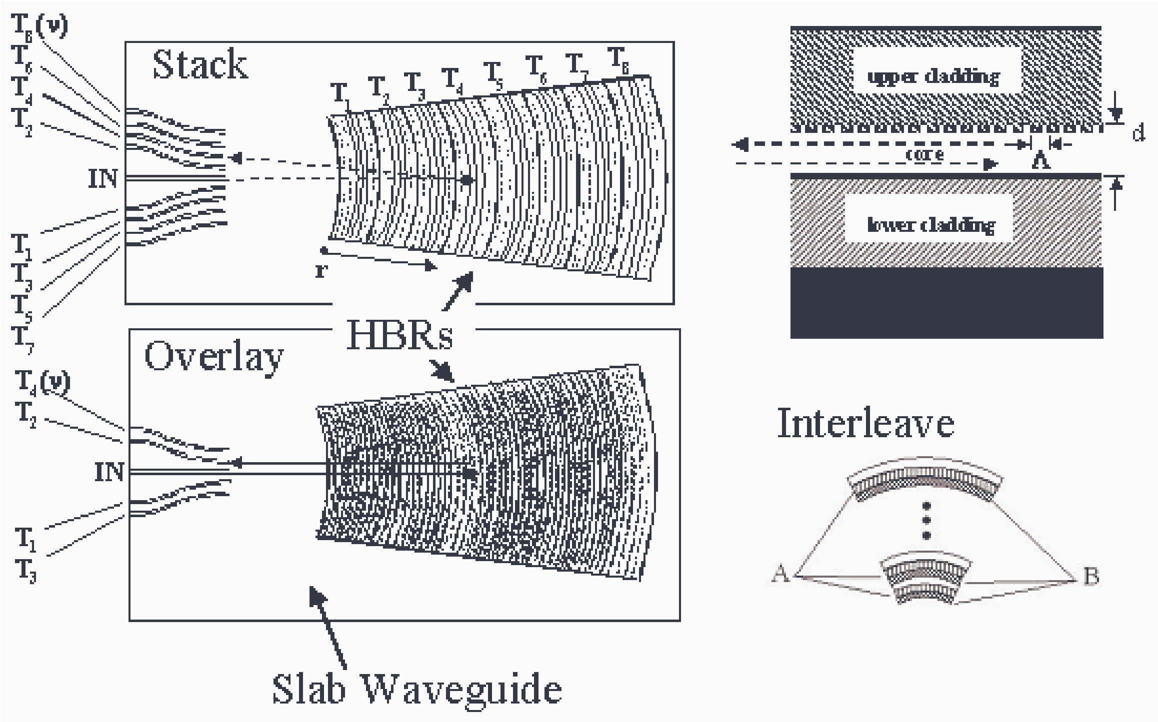

Figure 2. Integration of multiple HBR devices in a single slab waveguide region.

A stacked array of HBRs is conceptually simplest. Multiple HBRs, each with separate spatial routing function, are positioned along the propagation direction of injected signals. In a demultiplexing operation, signal incident through a common input port interacts successively with the HBRs and each HBR back-diffracts signals within a specific channel bandwidth to a design output port. Since spectral resolution of retroreflecting HBRs scales with the inverse HBR length, the stacked geometry provides the lowest per channel resolution (for fixed overall device length) of the various approaches to combining HBRs.

HBRs can also be superimposed and share the same waveguide real estate. This scenario has the advantage that the spectral resolution of the overlain HBRs is all set by the inverse of the full device length (giving about 10 GHz resolution in a 1-cm-long silica based HBR). Since integrated holographics most effectively involves simple binary etch, however, provision must be made in overlaying HBRs to prevent actual intersection or overlap of individual diffractive contours. With strictly binary etch, overlapped diffractive contours are not accurately rendered. To avoid direct overlap of diffractive contours, the contours of individual HBRs may be written with a small fill factor (see Figure 1) so that a small percentage of the contour is actually etched. Additionally, the computer design algorithm is tweaked to look for overlaps between written contour regions and eliminates them by spatially shifting one or both of the affected contour regions to eliminate the intersection. Multi-layer etch, though more costly and difficult from a fabrication point of view, may potentially be employed to enable some degree of actual diffractive contour overlap.

Interleaving of HBRs provides yet another alternative approach to providing device function with multiple HBRs. In interleaving, HBRs may all span the entire length of a device, but each HBR is divided into a multitude of typically non-contiguous segments with segments of other HBRs lying in between. As in the overlain case, the resolution of interleaved HBRs may be limited only by the size of the entire HBR region. Interleaved HBR diffractive contours may be fully written without danger of intersection and hence incorrect rendering, since diffractive contours of only one HBR are written within the boundaries of each interleaving segment. On the other hand, interleaved HBRs are like sampled gratings and will typically exhibit extraneous spectral features that may possibly conflict with intended device function.

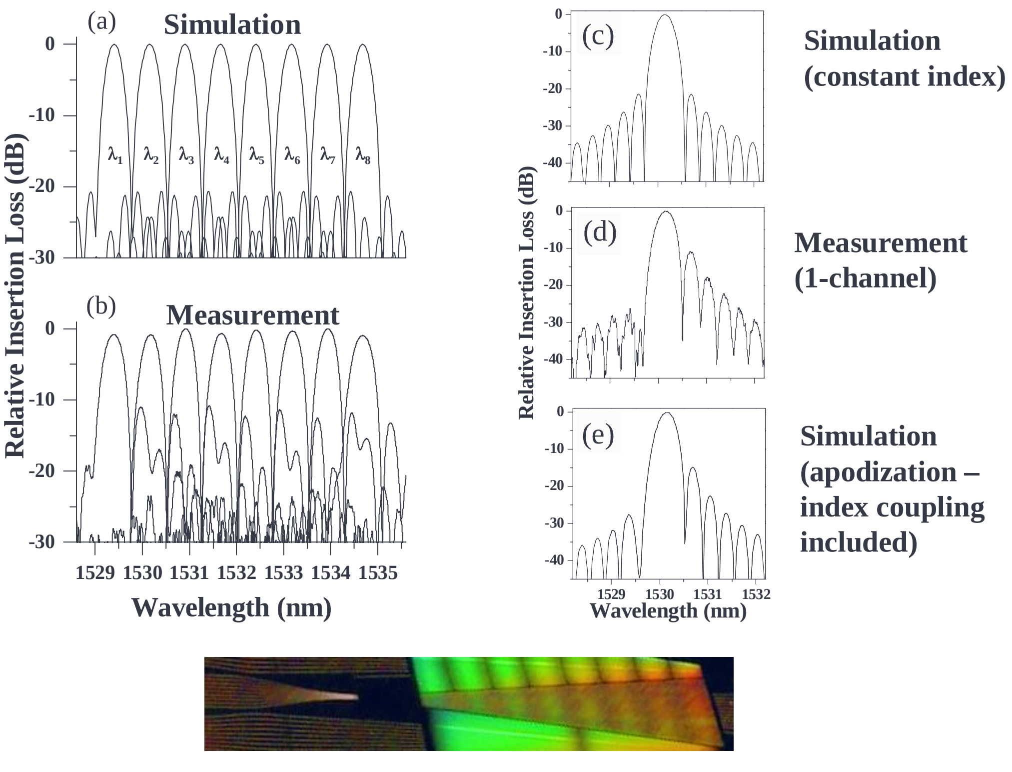

Figure 3. Simulated and measured spectral passbands of eight-channel multiplexer with device photo at bottom.

In Figure 3, the spectral transmission functions for an 8-channel HBR multiplexer are shown[5]. The HBRs are apodized with the partial fill amplitude control method described above. Simulations that do not account for the coupling between effective refractive index and contour fill percentage are shown in Fig. 3a. Measured spectral transfer functions of a fabricated device are shown in Fig. 3b. The spectral passband asymmetry exhibited in the fabricated device result from coupling of amplitude apodization and effective refractive index as described above. This coupling was not included in the computer algorithm employed to design this particular device. Fig. 3c simulates the passband expected for one channel ignoring coupling of diffractive contour fill and effective refractive index. Fig. 3d shows the passband of the actual device. Fig. 3e shows the passband expected from the actual design when coupling between contour fill and effective refractive index is included in the modeling. The accuracy of the model in predicting fabricated device performance clearly indicates that improved function will follow from incorporating apodization-index coupling into design models. Alternatively, correlated line set apodization, which largely eliminates coupling of refractive index and amplitude apodization may be employed.

2.2. Waveguide Sampled diffractive structures.

In an arrayed waveguide grating (AWG) device, an input signal is split between a family of channel waveguides of carefully ramped length and then recombined via diffraction. The recombination process proceeds in a manner similar that observed when light reflects from a concave diffraction grating. One obtains a mapping of signal wavelength to output position along an output plane.

One can combine some elements of the AWG architecture with HBR concepts to produce a useful family of devices we refer to as waveguide sampled HBRs. In Figure 4, left, a simple HBR structure is shown with inscribed channel waveguides positioned so that the channel waveguide axes run locally perpendicular to the diffractive contours. In a waveguide sampled device, the HBR structure is etched away except where the channel waveguides are located. One

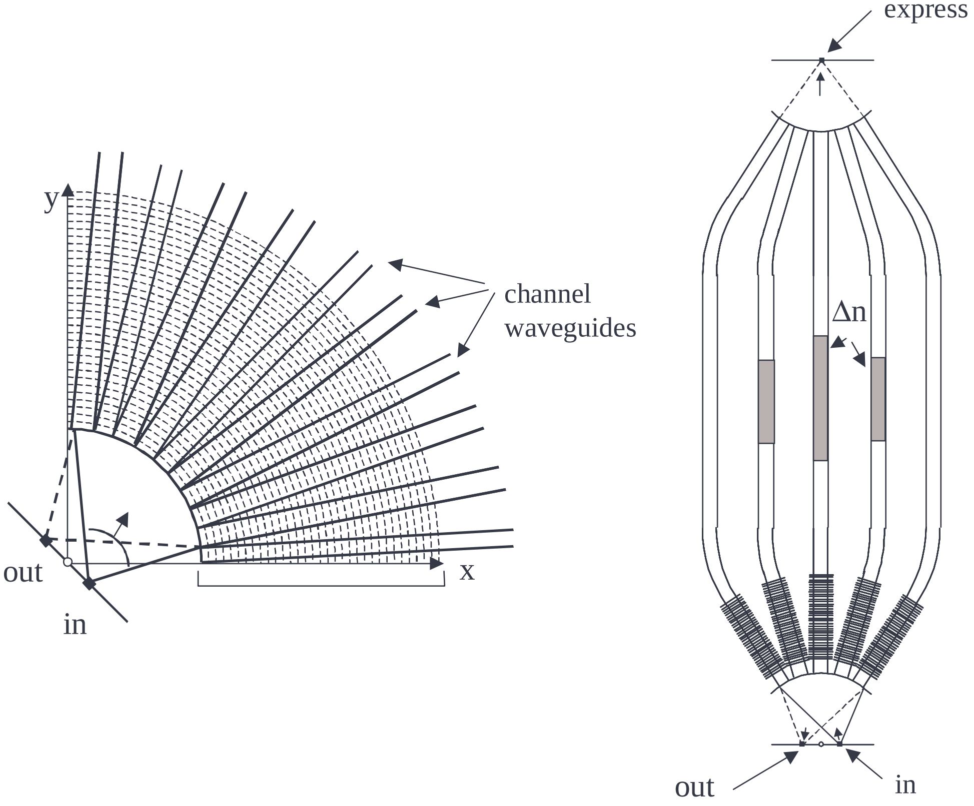

Figure 4. Left: HBR with schematic channel waveguide sampling. Right: Waveguide sampled filter with express.

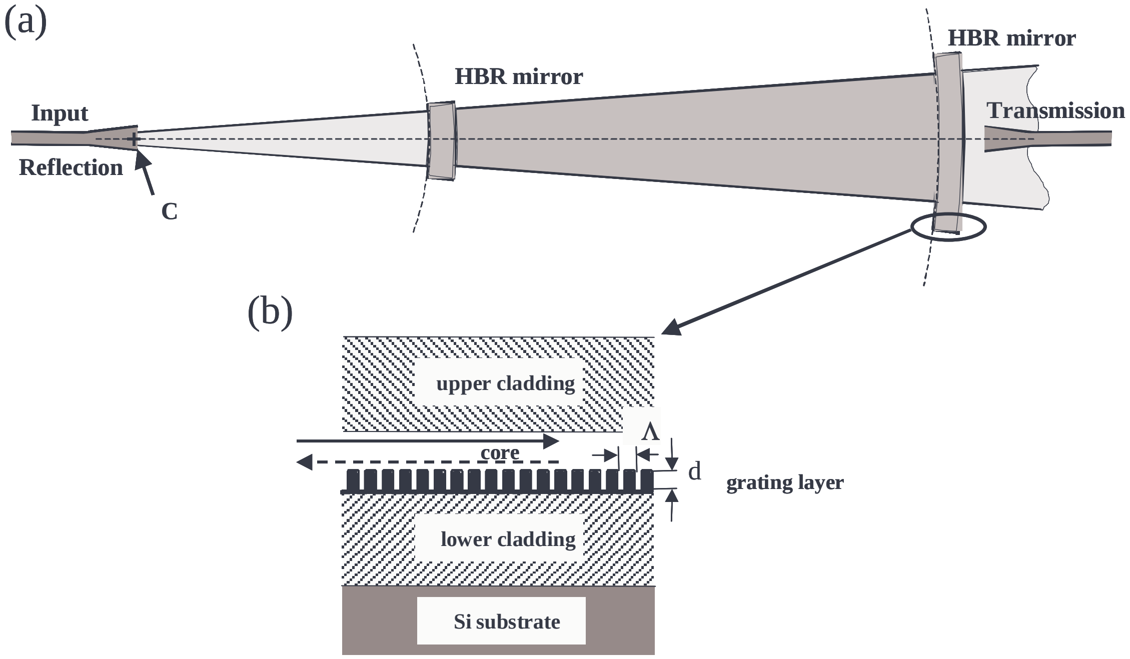

Figure 5. Integrated asymmetric concentric cavity (a) with internal slab waveguide design (b).

can think of the channel waveguides and the gratings they contain as producing a back reflected signal that provides a sampled copy of the signal back reflected by the fully implemented HBR structure. In the waveguide sampled device, however, one has additional degrees of freedom that do not exist in the fully 2D structure. For example, at the right of Figure 4, we show a waveguide sampled HBR wherein the sampling waveguides continue and are recombined as in an AWG, except that the through signal is processed in the zeroth grating order and is therefore wavelength insensitive. Variations in the channel core index or other means may be implemented so that the waveguide array acts as a simple essentially wavelength independent lens directing the through signal to a specific output port.

At the entrance to the waveguide array, the HBR segments, which may be offset for precise phasing and focusing of the backreflected signal, act to select one or more wavelength bands and route them to a desired port. Fabrication of multiple HBR grating structures in the waveguide array, with separate relative phasing of each, allows multiple bands to be back directed to different output ports. The waveguide sampled HBR thus behaves as a one- or multi-channel drop filter with express. Many variations of waveguide sampling of 2D focusing structures are possible providing control of both reflected and transmitted signals. Phase shifting devices at the ends of the waveguide arrays provide for dynamic switching of either express or back reflected signals to desired ports. Also, symmetric placement of diffractive structures at both ends of a sampled device allow for add and drop function with express in a single device.

2.3. Resonant-cavity structures

Integrated holographic mirrors can be designed to have high reflectivity over targeted bandwidths. This being the case, it is possible to design optical resonators analogous to those in widespread use in the context of 3D free-space optics. By projecting familiar cavity designs into two-dimensions, one can obtain analogs of standing-wave, ring, stable, and unstable resonators used as laser cavities, frequency references, filters, etc. Planar cavities can be configured to accept a range of spatial modes – just like the well-known free-space confocal Fabry-Perot filters, which are famous for their light collecting power.

In Figure 5a, we show an asymmetric concentric cavity of approximately 4 mm total design length. The common center of curvature of the diffractive contours comprising both HBR based mirrors is denoted by the point labeled “C.” Light

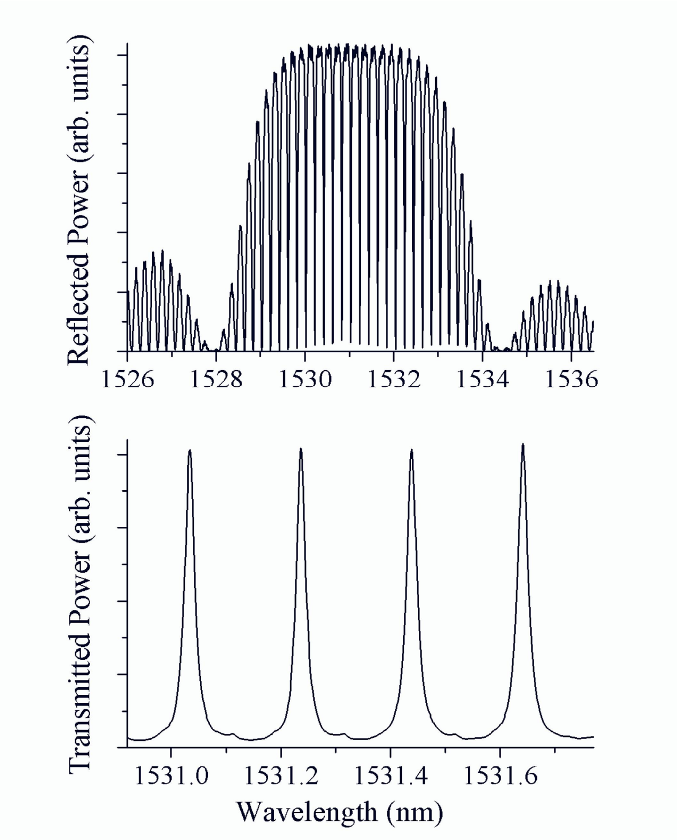

Figure 6. Reflection and transmission spectra of cavity shown in Figure 5.

entering a flared channel waveguide from the left is well matched to the cavity mode and one can observe a back reflected signal that propagates back along the input channel and a transmitted signal diverges out the right end of the cavity. Figure 5b, shows the planar waveguide in the region of one of the cavity mirrors. A dual-layer core is employed, with the lower core layer containing the etched diffractive contours and having a relatively higher refractive index to concentrate the slab waveguide mode in the region of the contour interfaces. The cavity mirrors were designed to exhibit moderate reflectivity. The reflected and transmitted spectra observed[6] from the fabricated device are shown in Figure 6.

The Q value of this fully integrated cavity is found to be approximately 10^5 and is limited entirely by mirror reflectivity. Simulations suggest that total round trip loss within the cavity is on the order of one percent, indicating that cavities with Q's in excess of 10^6 should be possible with higher reflectivity mirrors. Such Q values compare very favorably with ring resonators and other fully integrable cavity solutions. Furthermore, the present cavity does not rely on fabrication critical evanescent coupling to a neighboring channel waveguide for access. Transverse spatial coherence is important in this cavity design. Observed performance indicates that mirrors and optical path lengths are true across the cavity aperture to the incredible level of $\lambda/20$.

SUMMARY

Integrated holographic devices combine the principles of volume holography, state-of-the-art patterning tools of the semiconductor industry, and planar waveguide technology to create a range of building block elements for future integrated photonic circuits. Integrated holographic building block devices are fundamentally different from channel waveguide and photonic crystal based devices and uniquely allow for the exploitation of the non-interactive nature of photons through design of circuits with intersecting and overlapping signal streams still uniquely controllable via wavefront and wavelength selective integrated holographic devices. Integrated holographic filters have much higher spectral resolution for a fixed device size than AWG-type filters and have the programmability of either thin-film or fiber Bragg devices. Integrated holographic filters are powerfully consistent with low cost fabrication via master-based stamping/nanoprinting/molding processes and therefore uniquely enable devices addressing low-end, high-volume datacom and computer-related communications. While not discussed in detail here, the integrated holographic device format is ideally suited to serve as a basis for optical interconnects as a hybrid chip layer or the board level. In closing, it should be noted that recently fabricated devices have demonstrated insertion losses limited only by coupling between access channel waveguides and external optical fibers and furthermore that suitable waveguide and internal design features produce essentially polarization independent behavior.

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