Integrated Photonics based on Planar Holographic Bragg Reflectors

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ABSTRACT

Integrated holographics is a novel photonics technology made possible by recent advances in semiconductor manufacturing technology and planar waveguide fabrication. The technology's corner stone, the holographic Bragg reflector (HBR), is a slab-waveguide based, nanoscale, refractive-index structure that merges, for the first time, powerful features of holography, such as single-element spectral and spatial signal processing and overlay of multiple structures, with a highly integrated environment. As a building block for photonic circuits, the HBR's holographic signal mapping comprises a unique and novel way of on-chip signal routing and transport that is free-space-like but fully integrated. Signals propagate and overlap freely as they are imaged from active element to active element - an architecture that eliminates the need for constraining electronics-style channel-waveguides and associated space requirements and opens the door to unique integrated photonic circuits of very compact footprint. Photolithographic HBR fabrication was recently demonstrated to provide complete amplitude and phase control over individual HBR diffractive elements thus offering the powerful ability to implement almost arbitrary phase-coherent spectral filtering functions. This is enabling to a broad range of optics-on-a-chip devices including compact multiplexers, tailored passband optical filters, optical switch fabrics, spectral comparators, and correlator-based optical look-up tables.

Keywords: Integrated Optics, Photonic Crystals, Fiber Optics, Distributed Bragg Reflector, Planar Lightwave Circuit, Photonic Bandgap Materials, Apodization, Lithography, Silica-on-Silicon, Holography, Wavelength Division Multiplexing.

1. INTRODUCTION

Traditional Volume Holography

Volume holography has long attracted interest as a basis of optical signal processing applications and devices since it allows the simultaneous spectral filtering and spatial routing of optical signals – a powerful inherent dual functionality. Volume-holographic devices incorporate both spectral and spatial functions into a single structure thereby offering a unique solution to a broad range of optical device design problems.

Yet, despite their inherent powerful dual functionality, volume holographic methods have not made widespread impact in device technology. Key to enabling their widespread implementation is the identification of fabrication means consistent with the complex micron- or submicron-scale diffractive structures needed, which at the same time can produce devices that are cost effective and of high reliability. Such a fabrication approach has been difficult to realize for fully three-dimensional structures, primarily because such structures must be written using optical interferometric methods. The latter are generally

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difficult and complex since they require high stability of writing beams and material properties which are often inconsistent with long-term device stability. Furthermore, the device functionality that may be obtained by optical interferometric fabrication is constrained by the availability of optical fields that can be physically realized, by the stability of such fields, and by recording material properties such as resolution.

Integrated Holographics

Integrated Holographics - a new direction in holographic technology conceived at LightSmyth – solves many of the problems that plagued traditional volume holography and have caused the so far limited implementation of holographic devices. Recent analysis at LightSmyth[1] has shown that two-dimensional holograms written in slab waveguides retain essentially the same spectral filtering and spatial transformation capabilities exhibited by their fully three-dimensional cousins. Significantly, the planar nature of waveguide-based holograms offers breakthrough fabrication pathways via standard semiconductor fabrication methods. Rather than interfering write beams in a recording materials, holograms are computer-generated via interfering of suitable mathematically modeled beams, laser-written to a reticle, and then transferred to the optical waveguide via deep-ultraviolet (DUV) photolithography. This approach enables unprecedented design freedom relative to the spatial and spectral hologram signal processing functions since essentially arbitrary model write beams can be used for hologram generation – disregarding whether practically available for use in traditional interferometric fabrication. Furthermore, silica and other waveguide materials of current interest comprise an extraordinarily stable and robust substrate.

The unique merging of three previously unconnected disciplines, volume holography, waveguide optics and DUV projection-photolithographic fabrication into a new field - *Integrated Holographics* - has only recently become practical with the advent of high-resolution photolithography (<250 nm resolution) and waveguide materials of sufficient quality. For the first time ever, the spectral and spatial signal processing power of holography can be harnessed to fullest extent in a robust fully-integrated environment making possible integrated holographic devices for a broad range of optical signal processing applications.

Building Blocks: Holographic Bragg reflectors

Planar holographic Bragg reflectors[2] (HBRs) constitute one building block of the *Integrated Holographics* technology. Figure 1, left side, illustrates the operational principle of the HBR device using a simple back-reflecting HBR device. Signals expand into a free space region of a slab waveguide after being launched from the device input port (here located at the endpoint of an access channel waveguide). After traversing the expansion region, light interacts with an array of diffractive contours comprising the planar hologram, which in the example of Figure 1 are trenches filled with cladding material that are located at the upper core-cladding interface of the planar waveguide. If resonant, optical signals are coherently backscattered to the device output port. Shown at the right side of Figure 1 is a device cross-section. The device is based on a single-mode core with thickness, h, of 2 - 4 μm, employs core-cladding index contrasts on the order of one to a few percent and operates in first diffraction order at 1.5 μm, yielding a contour spacing, Λ, of about 500 nm. Typical trench depths, d, are 400 – 800 nm.

Significantly, the shape of the hologram contours shown in Figure 1 may be optimized to efficiently couple virtually any input field mode to any output field mode. Contour optimization is undertaken via the methods of computer-generated holography, i.e. deriving the hologram diffractive contours from the interference pattern between model input and output beams of desired spatial and spectral properties. The resulting optimized hologram contours allow one to efficiently image and route signals in very general situations including non-paraxial scenarios, e.g. 90° bends or forward focusing lens-like structures that convert diverging inputs to converging outputs without change of beam direction.

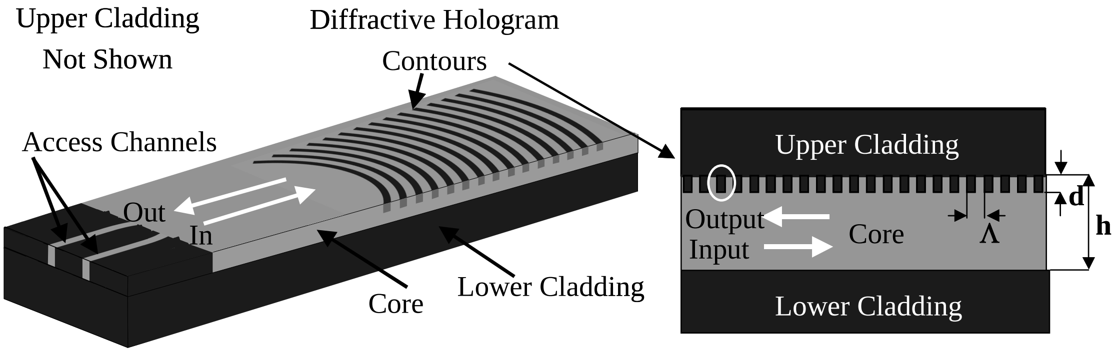

Figure 1. Left side, 3D schematic of simple holographic Bragg reflector. Right side, HBR cross-section.

DUV-Photolithography and "Effective Greyscale" Apodization: Enabling Centimeter-Scale Spatially Coherent Holograms with Amplitude and Phase Control of Individual Lines

After computer optimization, holograms are laser-written to a reticle and then transferred to the silica-on-silicon optical waveguide via DUV photolithography. Recent LightSmyth results have conclusively established, for the first time ever, that the photolithographic fabrication approach provides fully spatially coherent control of diffractive features on centimeter-length scales making centimeter-scale planar holograms a reality[3,4]. The spatial coherence properties demonstrated as part of published work constitute a world record in this quantity. Experimental results demonstrated are consistent with nanometer feature placement accuracy.

Virtually arbitrary device spectral transfer functions may be implemented via LightSmyth's *effective greyscale* approach to device apodization[5,6]. Figure 2 shows how amplitude control of individual hologram contours is achieved by partial writing of the latter, with the written contour fraction proportional to the

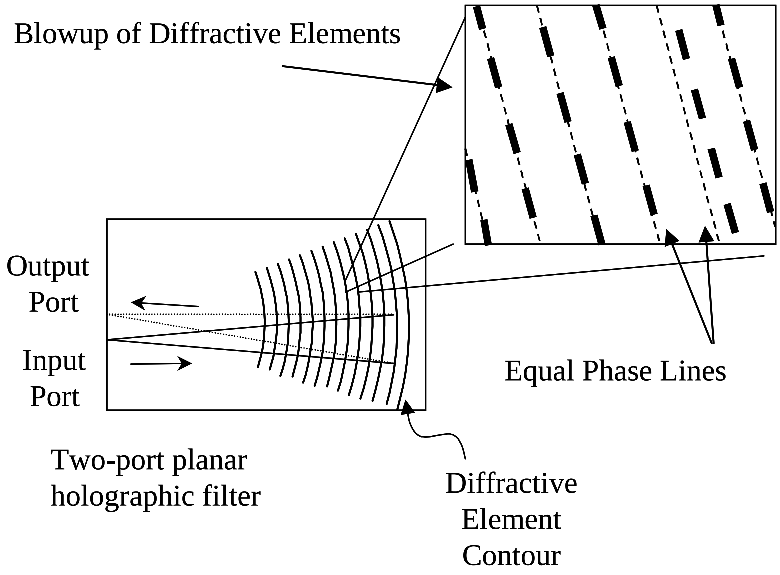

Figure 2. Top view of a planar holographic Bragg reflector illustrating the concept of "effective greyscale". Individual hologram contours are amplitude apodized by partial writing. Phase apodization is achieved by appropriate spatial offsets.

desired effective reflection coefficient. Significantly, the partial writing of hologram contours also allows one to overlay several partially written hologram on the same real estate. Phase control of individual contours is obtained by offsetting by an appropriate spatial amount the diffractive contour from its nominal positions dictated by the $\lambda/2$ – element spacing.

In the limit of weak to moderate reflectivity, device spectral transfer function and effective complex reflection amplitude as function of depth into the hologram form a Fourier transform pair - an approach that allows one to shape the HBR's passband via tailoring of the reflection properties in the spatial domain. For the design of highly reflecting devices, tools established in the design of fiber Bragg gratings are used. The *effective greyscale* approach has the inherent advantage of being fabrication friendly since it can be implemented with a uniform etch depth. The ability to manipulate both amplitude and phase of individual diffractive contours with the precision afforded by lithographic fabrication is unprecedented and has recently been applied to the design of several types of multiplexers[7] and filters[8], examples of which are shown in Figure 3.

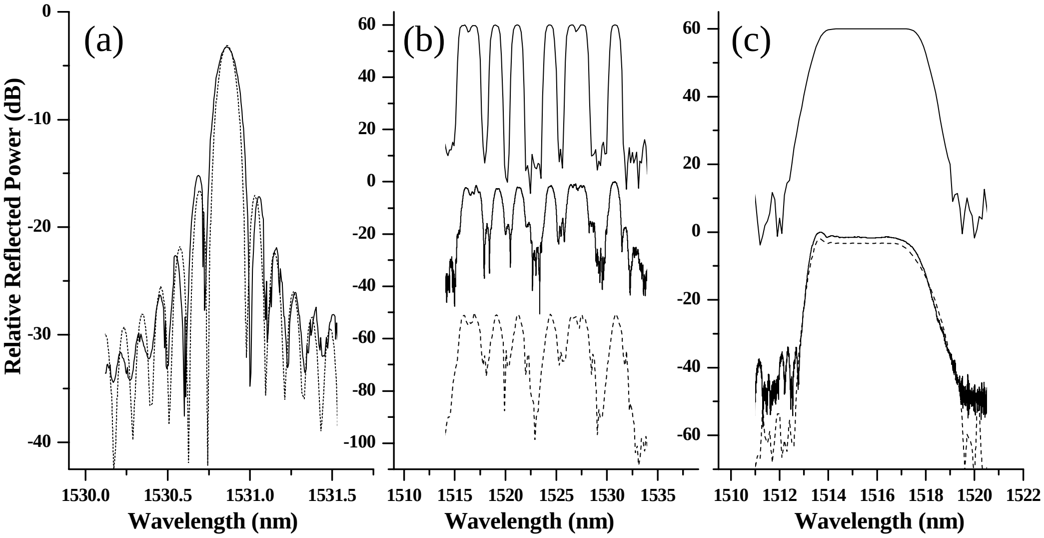

Figure 3. Measured and simulated spectral transfer functions of HBR devices showing various features: (a) Fourier-transform-limited high spectral resolution indicating feasibility of centimeter-scale HBRs, (b) complex multi-peaked spectral transfer function, important for applications in Optical Code-Division Multiplexing (OCDMA) or spectral comparison, (c) Flat-top passband filter. Solid lines, measured spectral transfer functions. Dashed lines, simulation results. Uppermost plots in (b) and (c) are projected transfer function, including correction for apodization-index coupling. *The excellent agreement between theory and data indicates essentially perfect reproduction of designs in fabricated devices.*

Distributed Photonic Circuits and "Native Mode" Photonic Signal Processing

Photons are not electrons. An obvious fact, yet its implications have not been thoroughly incorporated into current visions of future photonic integrated circuits, which center on wire-like channel waveguides and crystal-like structural analogs. Electrons interact strongly with each other and their environment. Electronic interaction leads to electronic bands and gaps crucial in electronic device operation. Electronic interaction also leads to the need for non-intersecting wire-like links between active electronic devices - a need which substantially defines allowed electronic integration formats.

In contrast to electrons, photons do not interact with another, leading to the possibility of circuits wherein photonic signal lines are delocalized and overlapping. This photonic property yields great freedom for the placement of active and passive devices and enables highly spatially-multiplexed devices of ultra-compact footprint. To enable photonic circuits that fully exploit the possibility of free signal overlap, a photonic transport fabric is needed that provides signal-specific guiding action.

Holographic Bragg reflectors constitute the building blocks of this photonic fabric. They form the basis of a unique kind of integrated photonic circuits. In these *distributed photonic circuits* – the name derives from the distributed nature of the HBR – photonic signal processing occurs on basis of both the photonic spectral as well as spatial properties. The spectral and wavefront–selective nature of the HBR allows tailored interaction with specific target signal modes, while non-matching modes simply pass without being affected. This novel holography-enabled type of signal processing makes possible an innovative photonic signal processing and transport approach that breaks away from popular electronic analogs such as wire-like channel waveguides and utilizes more effectively the fundamental and uniquely photonic properties[9,10].

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