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The Composite Structure of Hologram and Optical Waveguide

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1. Introduction

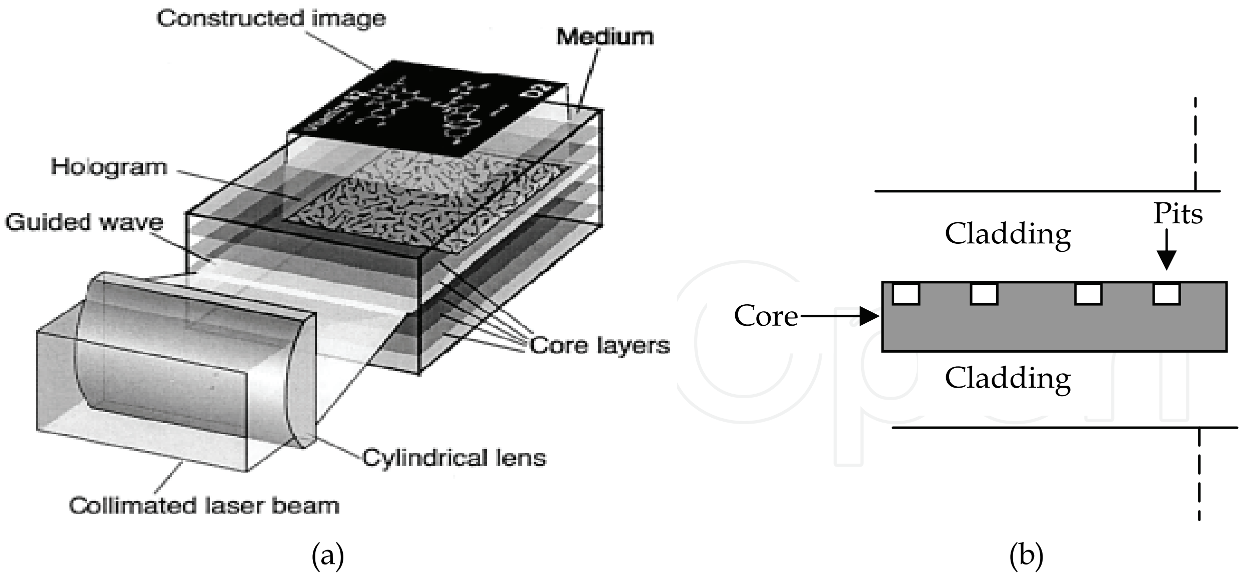
Optical holography is an excellent technology which can be applied in many fields, such as 3D-displays, information storage, products packaging, interferometer survey, optical connection and computer and so on. The conventional holography include reference wave, object wave and diffracting wave. These optical waves are spatial light and the whole hologram set up is fair size. The optical waveguides which are set up in optical routs can be integrated into a mini-chip. A new class of holography is proposed by many researchers [Suhara, et al., 1976; Putilin, et al., 1991; Singher & Shamir, 1994], in which the evanescent part of a guided wave or the guided wave in a waveguide is utilized as the reference wave or the illuminating one. This kind of hologram is defined as “waveguide hologram”, and it has significant advantages in integration, wide field of view, compactness and other special functions. In this chapter, three sections are used to introduce the new development of waveguide hologram in the optical memory, optical connection and see-through planar displays fields.

2. The multilayered waveguides and holograms structure (MWH) for memory

With the development of information era, the dramatic increasing of information data needs new technologies of high density data storage. The holographic storage is regarded as a promising candidate for the next generation of optical memory. However, the conventional reconstructed holographic system includes reference wave and diffracting wave, which are spatial lights. The whole hologram system devices are large, so they are not suitable for personal use. The commercially available optical compact disc (CD) products have many advantages and play a key role in data storage area. But the data density of the optical disc can be hardly increased. We also know that the waveguide holography offers many advantages compared with conventional holograms. Waveguide holograms provide capability for the recording and reconstructing of holographic images or data information with light which propagates along optical waveguides. A higher image-to-background contrast and diffraction efficiency can be obtained because the direction of diffracted light wave is *vertical* to the illuminating light wave. Furthermore, waveguide holograms provide minimized illumination space and obstruction-free viewing. Therefore, multilayered waveguide and hologram technology is a promising candidate to solve the problems for the next generation of optical data storage systems, many researchers have focused on this work[Imai, et al.,2003; Ishihara, et al., 2004; Mitasaki & Senda, 2006; Yagi, et al., 2007; Yagi, et al., 2008].

2.1 The principle of multilayered waveguide hologram memory

At present, there are many types of multilayered waveguide hologram structure. In this chapter, only three main types of multilayered waveguide structure for optical data storage are introduced. The first is shown in Fig. 1(a), a multi-layered structure where a layer with a high refractive index (core layer) and a layer with a low refractive index (clad layer) are alternately stacked. The hologram structures are fabricated in each waveguide core layer or on the surface of waveguide core layer in the style of pits, bumps or bubbles, as shown in Fig. 1(b). In general, they are computer-generated planar holograms. When light is introduced to this structure, the light is confined in the core layer and then propagates along waveguide core layer as reference wave. The diffracted light become spatial wave propagating in free space and containing the information from holograms, and the reconstructed images focused on the special position above of MWH, a detector such as charge-coupled device(CCD) is located at this position without any optical lenses. Because that the reference light can be confined in a target layer, and hence, the other layers do not interact with the reference light, so there are no or low crosstalk between different interlayer from the diffracted object light from one of target waveguide layer. A 100-periodic multilayered structure has been successfully fabricated and a data density of 100Gbit/inch2 can be achieved in the reference [Imai, et al., 2003], Fig. 2 shows bumps on the surface of waveguide core layer by Scanning electron microscope (SEM).



(a) (b)

Fig. 1. (a) The firstly type structure of multilayered waveguide holograms, (b) Schematic diagram of element layer in MWH

The second type of multilayered waveguide hologram structure element is shown in Fig.3 [Mitasaki & Senda, 2006; Gao, et al., 2007], which is composite of a holographic data recording layer, a core layer(high refractive index n1)with waveguide grating, and two cladding layers with lower refractive index n_2, underneath the data recording layer. The light was coupled into the waveguide core at the edge of MWH by cylindrical lens and then excited guide-mode light which propagated along the waveguide core. When meeting the waveguide gratings, the guide-mode light are diffracted into free space light as reference wave of holographic data recording layer. When the hologram recording layer is illuminated with these reference waves, the data information or holographic image is reconstructed by diffracted light of hologram recording layer. The direction of diffracted light of waveguide gratings can be different for each layers, thus the angle of β of light can be changed according to the structure of waveguide gratings for each layer. This type MHW also can be applied in three-dimension displays when many waveguides layers are illuminated at the same time.

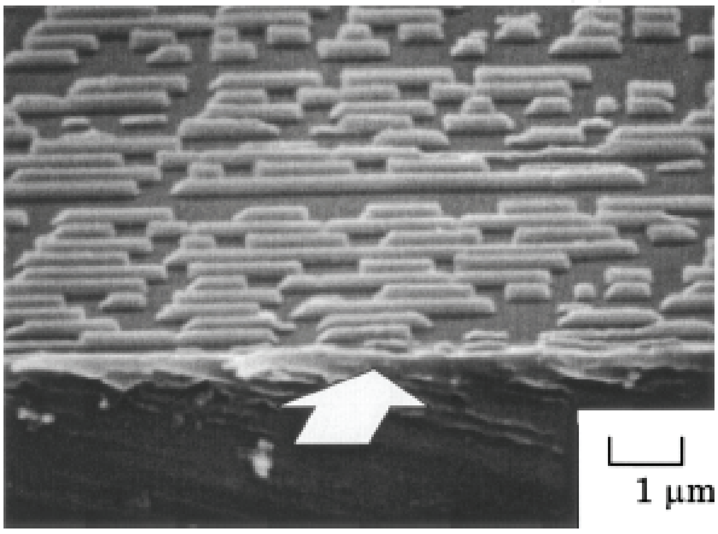


Fig. 2. SEM micrograph of a waveguide hologram (Imai, et al., 2003)

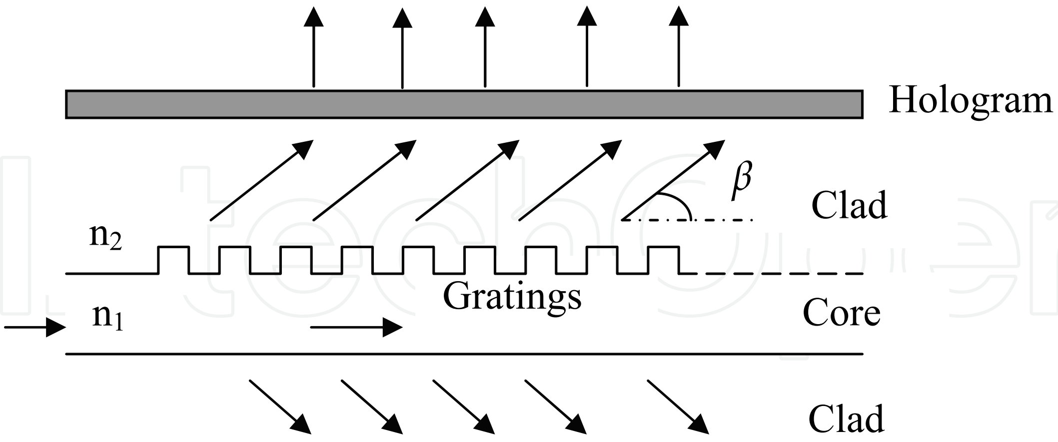


Fig. 3. Another type structure of multilayered waveguide holography element

Until now, we just discuss the type of MWH memory in which diffracted lights are coherent ly interfered. Guo et al. proposed a waveguide multilayered optical memory (WMOM) with bits stored as a refractive index change [Guo, et al., 2007], such as in Fig.4. The principle of reading data from a WMOM is based on scattering light from waveguide defects. In Fig. 4, when the incident light is coupled by the reading system L_1 into the core of the nth- *D*n layer waveguide element of the waveguide multilayered disc (WMD), a series of guided modes and radiated modes will be excited. It is assumed that only guided modes remain and that radiated modes are attenuated to zero before meeting bits. Partial powers of guided modes confined in the core of the waveguide will be scattered from the core by bits. Hence, light scattered by the bits recorded in the core of the *D*n layer waveguide element of the WMD will form an array of bright dots against the dark background. The dot array is imaged with a confocal microscope, and only the light scattered from the bit located at the focus of the confocal microscope is collected effectively by a detector and converted to electric signals for further processing. This memory system includes a confocal microscope, so the cost of this type of waveguide multilayered memory would be higher.

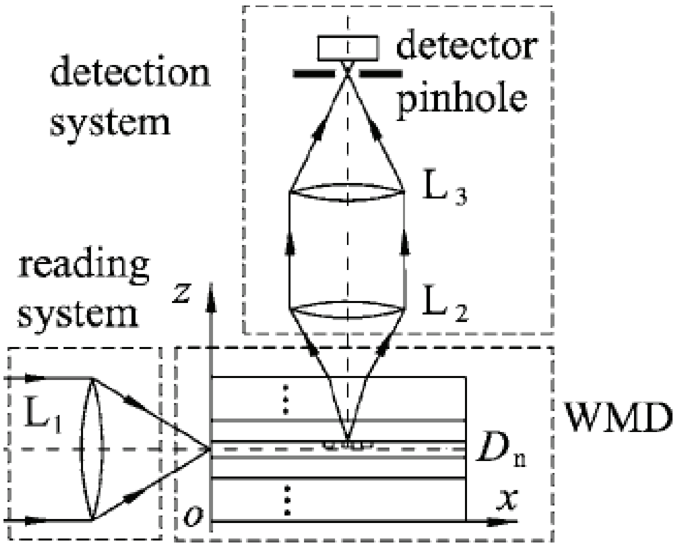


Fig. 4. Schematic diagram of a waveguide multilayered optical memory

2.2 Design methods of MWH

Generally, waveguide-hologram is based on computer generated hologram (CGH), especially for the first type MWH. Because information is implied by the style of pits or bumps on the surface of waveguide core layer or in the waveguide core layer, the distribution and shape of pits or bumps affect the quality of reconstructed image or data information. A waveguide hologram is a type of off-axis hologram where a guided wave is diffracted into free space, thus the reference light is guide-wave light propagated along the waveguide core layer and the diffracted light propagates along the direction normal to the waveguide core layer according to the distribution of bumps or pits. In a free-space CGH, the dimension of a rectangular element is typically of the order of more than ten times the optical wavelength. In order to effectively outcouple a guided wave, however, a grating period of wavelength dimension is preferred, thus the pits or bumps in rectangular element is small at the dimension of subwavelength.

In order to make diffracted light carry storage information, the bump or pit pattern needs to be designed by CGH method [Yagi, et al., 2008]. The guided-wave light disturbance in the waveguide plane can be represented by a scalar function $U(x,y)$ and the image detector plane can be represented by $V(x,y)$ .When the desired image is represented by a light intensity distribution, $I(x,y)$, can be expressed as:

$$I(x,y) = \left|V(x,y)\right|^2 \tag{1}$$

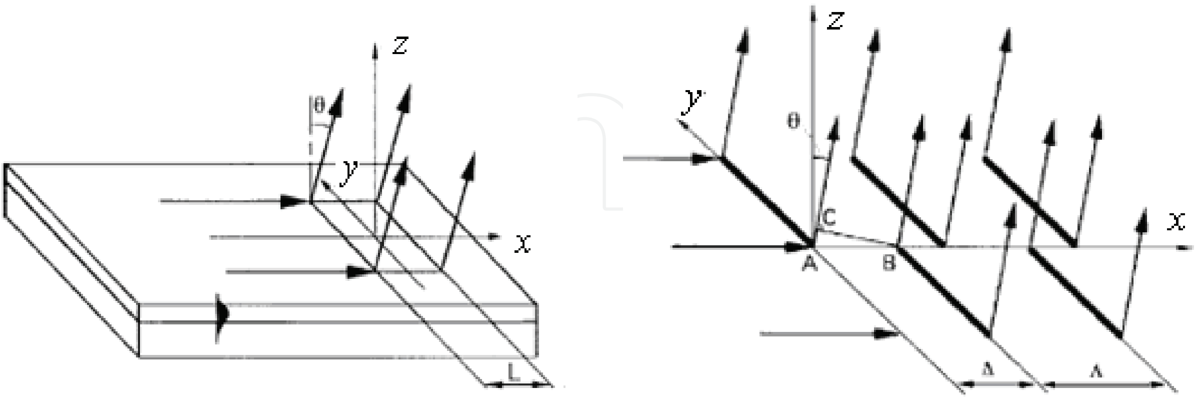
Because of the image detector parallel to the waveguide, then the relations is

$$V(x,y) = \iint G(\xi - x, \eta - y)U(x,y)d\xi d\eta \tag{2}$$

Where G is a weight diffracted function such that

$$A\frac{\exp(jk\sqrt{x^2+y^2+d^2})}{x^2+y^2+d^2} \tag{3}$$

Here d is the distance between the plane of image detector and the waveguide storage layer. A is a constant. As V(x, y) is a convolution of U(x, y) and G(x, y), we can obtain U(x, y) for a given V(x, y) by Fourier-transform calculations. The next step involves finding a way to modulate the bump pattern and thus generate a light, represented by U(x, y), from the guided wave. The area of the bump pattern can be divided into minute square cells whose size at the level of micrometer. The above calculations are performed with sampling at this interval. The wave function of each square cell is $U_{ij} = U(x_0 + \delta i, y_0 + \delta j)$ by the magnitude a_{ij} and the phase ϕ_{ij} , where $U_{ij} = a_{ij}\exp(j\phi_{ij})$. In each cell, such as in Fig.5, the lines of bumps are perpendicular to the propagation direction of the guided wave so that the total length is proportional to a_{ij} and the locations of the lines are shifted in the propagation direction according to ϕ_{ij} .Then the drawn bump pattern works as a hologram that generates the wave represented by $U(x,y)$ as the object wave from the guided wave, which is the reference wave. Such a hologram may be regarded as a type of Lohmann's binary hologram.
We also know that the data information are implied by style of pits or bumps at the surface of waveguide core layer, and the pits or bumps are usual fabricated by using of polymers material; thus this type of hologram is of phase modulation. Each pit or bump in a unit cell can be designed by using an array of rectangular elements each containing a dislocated binary phase grating [Li, et al., 1996].



(a) (b)

Fig. 5. (a) Schematic diagram of free space light coupled from guided-wave light in a waveguide hologram. (b) Magnified picture describing the geometry of a fraction of the waveguide grating in (a). The grating period is Λ , and the two sections of the grating, separated by the x axis, have a relative dislocation of Δ in the x direction.

The phase-matching condition must be fulfilled between the guided wave and the radiation wave:

$$n_{eff}k_0 + 2\pi m / \Lambda = nk_0 \sin\theta \qquad m = 0, \pm 1, \pm 2, \cdots \tag{4}$$

Where n_{eff} is the effective refractive index of guided-wave and n is the refractive index of the material within which the diffracted light propagates, θ is the radiation angle with respect to the normal of waveguide, such as in Fig. 5(a). $k_0 = 2\pi / \lambda_0$ and λ_0 is the free-space wavelength. M is the order of diffraction. In order to increase the output efficiency of diffracted light, only the -1st diffraction order satisfies the equation (4) when m= -1.Therefore, the grating period Λ (the unit cell size) must satisfy,

$$\lambda_0 / n_{eff} \le \Lambda < \lambda_0 \tag{5}$$

In Fig. 5(b), the unit cell is divided into two sections. Each section of the grating acts independently as an outcoupler, and the grating grooves in the two sections are relatively dislocated by a distance Δ along the guided wave propagating direction u. The grating period (Λ) satisfies (5). According to Fig. 5(b), there is an optical path difference, δL, between the radiation light outcoupled by two sections of the grating, which can be expressed as

$$\begin{aligned} \delta L &= n_{eff}\overline{AB} - n\overline{AC} \\ &= (n_{eff} - n\sin\theta)\Delta \end{aligned} \tag{6}$$

Taking into equation of (4) and noting that m= -1, the phase difference between the diffracted light, $\delta\phi$, as

$$\delta\phi = k_0 \delta L = 2\pi\Delta / \Lambda \tag{7}$$

It shows that a phase shift $\delta\phi$ can be introduced by a grating dislocation Δ, and there exists a linear relation between $\delta\phi$ and Δ. Fig. 6 shows a computer-generated waveguide hologram (CGWH) structure by this method.

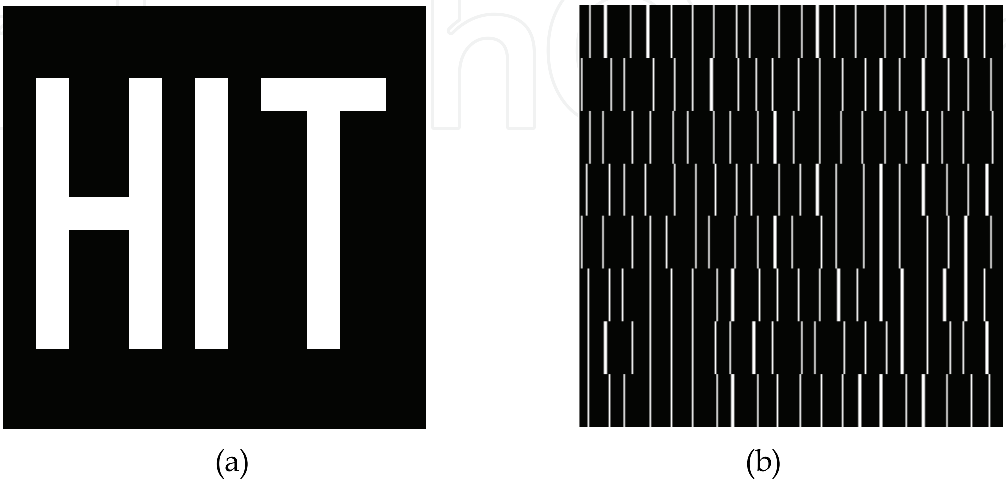

(a) (b)

Fig. 6. (a) The desired diffraction pattern, (b) a fraction of CGWH.

Yagi et al. discussed an optical design for multilayered waveguide holographies that utilizes an orthogonal aperture multiplexing (OAM) technique [Yagi, et al., 2007]. With OAM holography, the diffracted lights first concentrate in small isolated areas on the aperture plane (dashed line) and then expand and overlap on the imaging plane (solid line), as shown in Fig. 7. All the multiplexed images are diffracted simultaneously, as depicted by the solid and dashed lines. Any designated page (solid line) can be read without crosstalk by blocking all the diffracted lights on the aperture plane except for one selected area because one isolated area on the aperture plane corresponds to one page.

Fig. 8 shows a schematic view of the direct imaging optics. The diffracted light passes through an aperture, and then expands and constructs an image on the imaging plane, where h is the distance between the imaging and aperture planes, *a* is the size of the square aperture, and θ is the angle of expansion from the aperture. The aperture and imaging planes are parallel. Also, both the centres of the aperture and constructed square image form a line whose direction is normal to both planes.

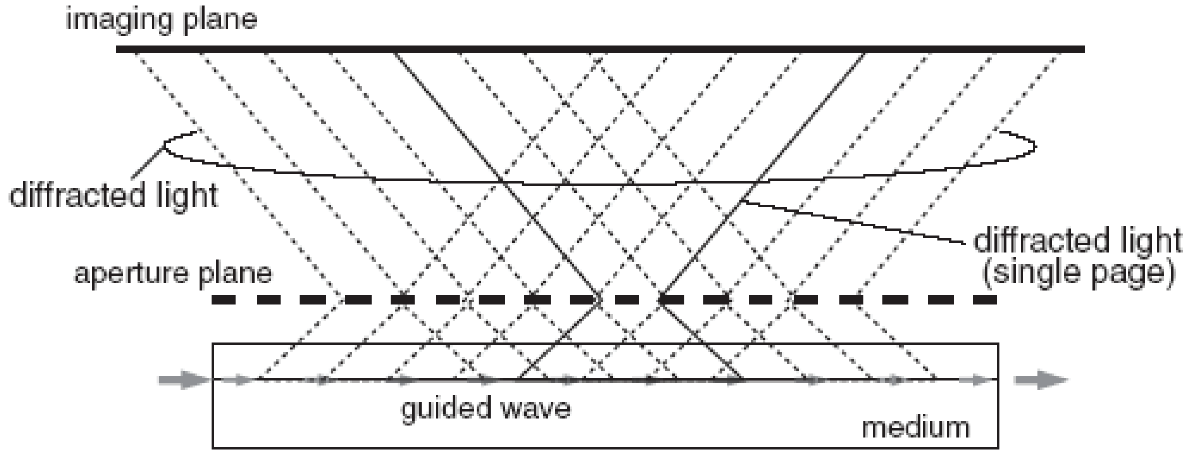


Fig. 7. Principle of orthogonal aperture multiplexing.

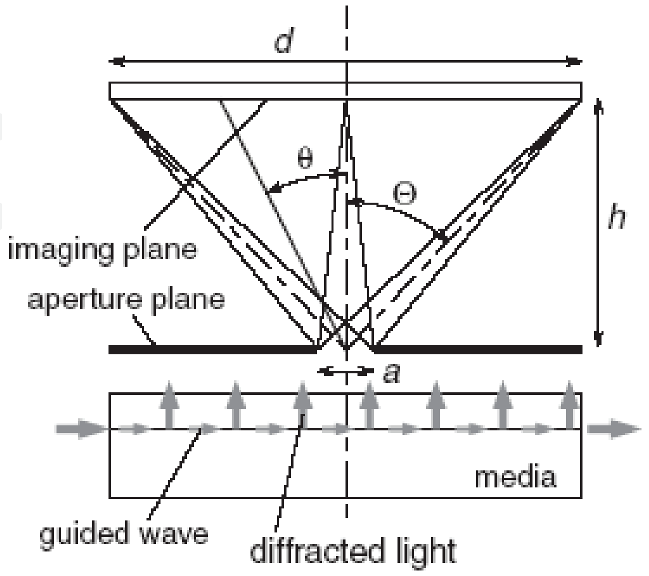


Fig. 8. Schematic view of direct imaging optics.

They discussed two types of optical design for OAM installed waveguide holograms. Both types can eliminate the need for an active focusing servo for imaging optics. The direct imaging optics offers a thinner driver, but it has a lower bit density and a shorter wavelength margin than the telecentric imaging optics. On the other hand, the telecentric imaging optics requires a thicker driver, but it offers a three fold higher bit density and a longer wavelength margin than the direct imaging optics.

2.3 Fabrication process of MWH

A multilayered waveguide hologram consists of a stack of single-mode slab waveguides with polymer as the main materials. So the fabrication methods of MWH are mainly concerned with the processing of polymer optical waveguides and the holograms. The size of pits or bumps of hologram designed by computer-generated hologram is small in dimension of subwavelength, so it is necessary to use the high precision micro-fabricating technology, such as photoresist-based patterning, direct lithographic patterning, soft lithography, embossing process and so on. In this section, we only introduce some key fabricating technologies for MWH.

- Spin-coating technology

Spin coating is an effective method to fabricate multilayered films with different thickness. We also know that the element of MHW is consist of the waveguide core layer with high refractive index of material and cladding layer with low refractive index of material. In this case, the substrate (rigid glass or flexible polyimide film) is mounted horizontally on a rotating platform. The substrate then spins very rapidly and the coating solution is dispensed onto it. The high-speed rotation throws off most of the solution, leaving behind a thin, uniform coating. Film thickness is precisely controlled by the rotational speed of the substrate. Faster rotation results in a thinner waveguide film layer. It is easy to form the film with thickness of 1~100μm by this method. However, Spin coating technology must be combined with other micro-manufacturing technology (such as photoresist patterning, reactive ion etching) to process computer-generated waveguide hologram.

- Lithographic patterning

Lithography is playing a critical role in micro- and nano-fabricated patterns for semiconductor devices and optics devices. It also can be adapted to process bits or bumps patterns on the surface of waveguide core layer in the computer-generated hologram. The techniques that can be used for patterning MWH included photoresist-based patterning, direct lithographic patterning, and soft lithography. The technology of photoresist-based patterning is seldom applied in fabrication of MWH, because that it needs cleaner room and reactive ion etching process, thus the cost of MWH is higher that other lithography patterning technology.

The direct laser lithography is a useful technique to fabricate a large planar areas with precision patterns, and it has the advantage of being maskless, allowing rapid and inexpensive prototyping in contrast to conventional mask-based photolithographic approaches. Mitasaki et al. proposed a write-once recording technique for MHW cards by laser directly writing, which can be suitable to record individual data easily in each MWH card [Mitasaki et al., 2006]. Soft lithography is a micro-fabrication technique that has been shown to generate high quality micro and nanostructures. It eliminates the use of costly and time consuming lithographic techniques and equipment. Unlike photolithography, it has flexibility in material selection, can be applied to large planar surfaces, and provided high precise control over chemistry of patterned surfaces. Some of the diverse fabrication methods known collectively as soft lithography include: replica molding, micromolding in capillaries, microcontact printing, and microtransfer molding.

- UV embossing process technology

The ultraviolet (UV) embossing process technology [Ishihara, et al., 2004] is preferred with the advantages of mass produce and low cost. To reconstruct holographic images, bumps need to be patterned at the interface between the cladding and the core. In this process, these bumps are patterned by UV embossing using a metal stamper, which has holographic patterns. By repeating this process, a multilayered waveguide structure can be fabricated. The process flow is shown in Fig. 9. Firstly, the metal stamper is fabricated by the conventional process used for stampers of compact disks (CDs) and DVDs. This stamper has patterns which are designed to produce holographic images. Two types of UV curable resin are prepared, whose refractive indices are adjusted to form the core and the cladding, respectively.

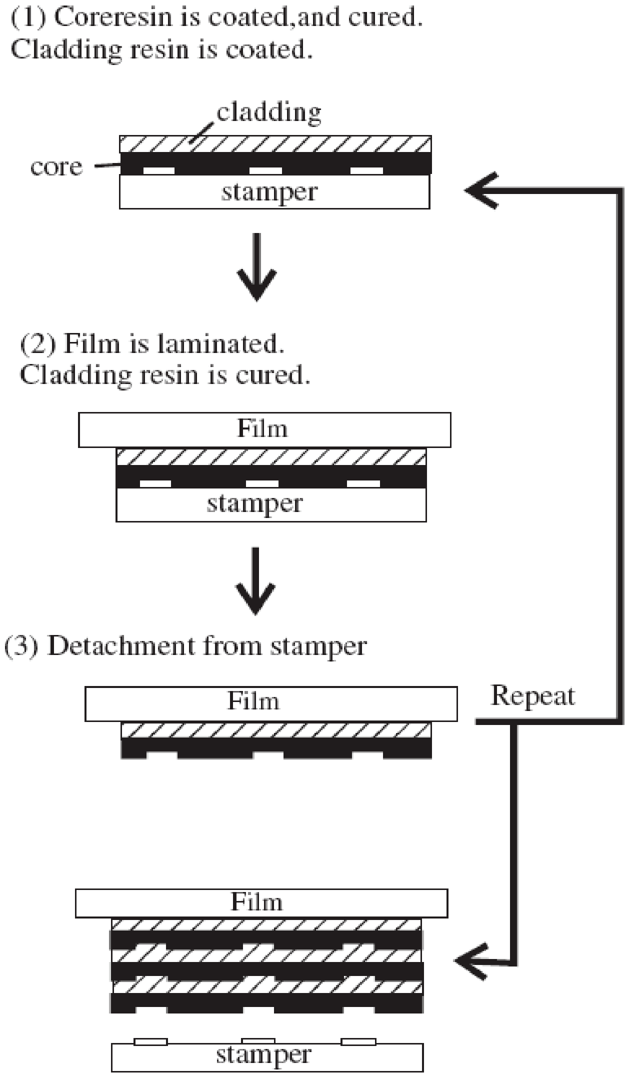


Fig. 9. Process flow of MWH

On the metal stamper, the UV curable resin for the core is spin-coated and UV-cured. Next, the UV curable resin for the cladding is spin-coated. A plastic film is laminated on it. After the resin is UV-cured, the film/cladding/core structure is detached from the metal stamper. By this process, the patterns of the metal stamper are replicated on the core layer surface. This process is repeated until the designated number of layers is fabricated. From the second cycle, the detached structure at the end of the former cycle is laminated instead of the plastic film, as shown in Fig. 9.

Using this process, Ishihara K. et al. have successfully fabricated a multilayered waveguide structure. Fig. 10 shows a picture of the 100-layer media structure. The thickness of the media is 2 mm. The thicknesses of core and cladding layers are 1.6 mm and 11 mm, respectively. 100-layer waveguides compose this media, and the holographic patterns are replicated in each layer.

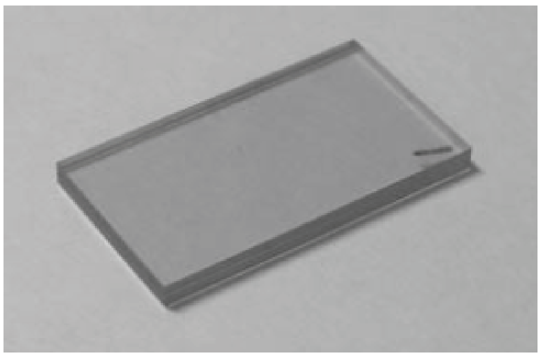


Fig. 10. 100 layer MWH , [Ishihara, et al., 2004].

2.4 Materials of MWH

Many different materials have been used in MWH in different mechanisms. In general, the materials for MWH need to have low optical absorption at the working wavelength. With the development of optical waveguide technology, many new materials with special functions have been introduced into this family. Several main optical materials are summarized in this section according to their mechanism.

- Optical polymers

Polymeric materials are particularly attractive in integrated optics because of their ability to be processed rapidly, cost-effectively, flexibility, and with high yields. Polymeric materials are allowed to form compact optical patterns by offering large refractive index contrasts and then easy to fabricate the planar waveguide structures. Some optical material, such as PMMA, PDMS, Epoxy resin and so on, now have been adopted in this field.. Polymer can be deposited by using spin coating or polymerization technique. Furthermore, the unique mechanical properties of polymers allow them to be processed by unconventional forming techniques such as molding, casting, stamping and embossing, therefore permitting rapid and low-cost shaping for waveguide formation.

- Dichromated gelatin

A normal gelatin film with less sensitive to light is sensitized through adding ammonium dichromate layer on it. Gelatin can absorb a very large amount of water and remain rigid, that means it swells. The chemical reaction happens on the interface of dichromated gelatin once it is exposed under light. The gelatin molecular chains in the exposed region have more cross-linking. These regions swell less when immersed in water. Rapidly dehydrated by exposure to alchohol, the dichromated gelatin film shows differential strains between regions of maximum and minimum swelling. These strains modify the way of local refraction. Information can be recorded as the refraction characteristics in exposed and unexposed zones.

- Photopolymers

Some monomer molecule materials can be polymerized either through direct interaction with light or through an intermediary photosensitizer. These materials are called as photopolymer. Once exposed under light beam with information, the polymerization of such material depends on the local intensity of the recording radiation. The diffusion of surrounding monomers takes place during and after the exposure. A uniform postexposure using a fluorescent light has also been applied to increase the diffraction efficiency and to desensitize the photosensitizer. The variation in polymer concentration corresponds to the refractive index modulation.

- Photoresists

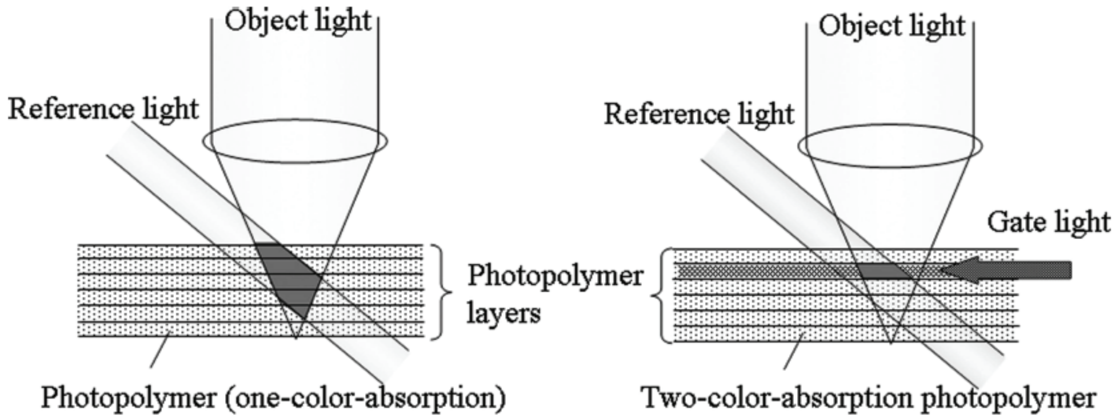
Photoresists are organic photosensitive materials, which can be classified into two types: negative and positive. The negative photoresists become insoluble in a solvent due to the polymerization. The rest unexposed area can be washed away. The positive case is just reverse when exposed on light. An image or holographic interference pattern is recorded on the surface of the photoresist layer through the insoluble and soluble area.

- Thermoplastic film

Thermoplastic film under a light beam produces a surface deformation of a transparent layer, which makes the phase of the light beam passing through the layer is modulated. The incident light pulses heat the thermoplastic layer to be molded according to the electrical field pattern.

- Two-color-absorption photopolymer

For the time being, two-color-absorption photopolymer is a new kind of recording material for MWH discs. It is attractive to be used in read-and-write MWH disks, because information can be only recorded on the target layer by illuminating the layer with a gate light, as shown in Fig. 11(b). Hirabayashi et al. of NTT photonics laboratories developed a



(a) (b)

Fig. 11. (a) Conventional holographic recording in multilayer photopolymers and (b) Two-color holographic recording in multilayer photopolymers

sensitive two-color-absorption photopolymer materials doped with is(silyl)pentathiophene as a two-color-photosensitive dye and 2,2-dimethoxy-2-phenylacetophenone as a radical photopolymerization initiator and working with a 660 nm interference light and a 410 nm gate light. In 2004, Fujitsuka et al. reported that oligothiophenes show two-color absorption, and Shimizu et al. recently found that the stepwise two-color absorption of the oligothiophene in a Zeonex (Zeon Co.) matrix followed by energy transfer to an aryl azide in the matrix is efficient for two-color recording and may be applicable to holographic recording in multilayer thin films.

3. Optical interconnections based on optical waveguides holography

3.1 Introduction to optical interconnection

The term “optical interconnection” is often called simply “optical wiring” or “optical interconnect” and can be interpreted in the broadest sense of the word as “any interconnection using optical means”. In term of linkages using optical means, optical fiber communication has been in practical use for more than twenty years, mainly for long distance links. In contrast, there has not been a strong need for short-reach optical links. However, as the problems of associated with hard-wired links become more apparent, this approach is gathering new focus. Optical interconnection is the most promising candidate for hard-wired circuitry. As optics become a major networking media in all communications needs, optical interconnects will also play an important role in interconnecting processors in parallel and distributed computing systems. Optical interconnect not only can provide much more connections than a traditional electronic interconnect, but also can offer much richer communication patterns for various networking applications. Such an optical interconnect can be used to serve as a cross-connect in a wide-area communication network or to provide high-speed interconnections among a group of processors in a parallel and distributed computing system.

Optical interconnections may be formed in substrates with waveguide structures and through the use of optical fiber, or in free-space either by beam spreading, or using holograms. The former is referred to as index-guided optical interconnection and the latter is referred as free-space optical interconnection. Fig. 12 depicts an example of free space interconnects [Gruber, et al., 2000]. A space between two circuit boards or a circuit board and optical interface board is purely empty. Light signals coming out from the sources propagate to designated location on the other substrate.

The purpose of the optical interconnection is to replace the electrical wire with the optical waveguide and associated optical devices. The smaller area the optical waveguide occupies on the chip area, the better integration the chip may have. All these approaches may be used to form reconfigurable interconnects with active components such as couplers for waveguides and optical fibers, modulators for beam spreading, and photo-refractive materials as dynamic holograms. Fixed interconnects are adequate for many purposes and don't require the use of active beam-steering components.

Free-space optical interconnections work in a three-dimensional volume in order to transport the signals to the desired locations. An earlier model of free-space interconnection is similar to a Fourier-plane imaging system with beam-deviating elements. The system has an array of sources in the object plane and an array of detectors in the image plane. Generally speaking, the light leaving the sources is deflected or fanned out upon passing a holographic element and deflected or fanned out again upon traveling through the hologram in the Fourier plane. Both the object plane holographic element and the Fourier plane hologram are partitioned into independently programmed regions, each of which functions as a sub-hologram, so that light from different sources or falling on distinct regions of the Fourier plane may be directed to different detectors in the image plane.

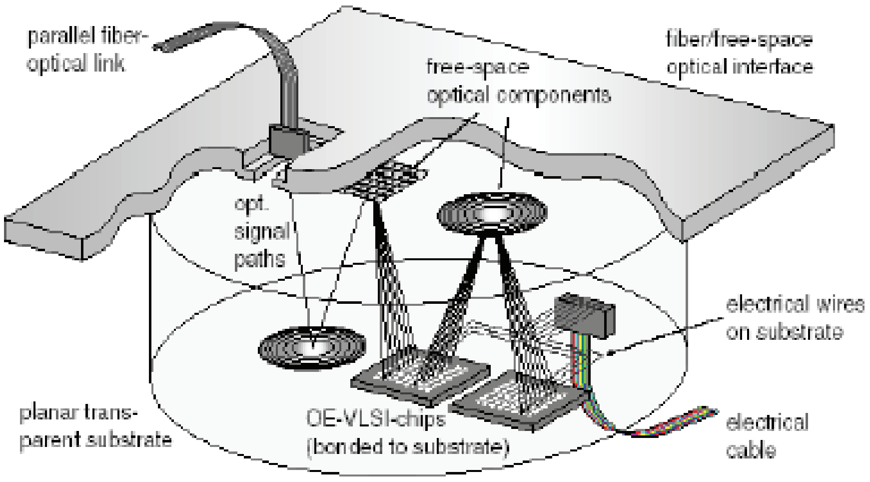


Fig. 12. Illustration of free space optical interconnect.

3.2 Optical interconnections based on optical waveguide holography

With the rapid advance of integrated optics, the importance of optical waveguides, which are the fundamental elements of optical integrated circuits, has been widely recognized. Optical waveguides are structures that confine and direct optical signals in a region of higher effective index than its surrounding media. By confining wave propagation, the waveguides provide communication between the electro-optical (E-O) transmitter and receiver, creating optical interconnects. Waveguide couplers play a key role for the realization of three-dimensional fully embedded board-level optical interconnection owing to their coupling of optical signals into and out of in-plane waveguides. A waveguide holographic grating can serve as a surface normal coupler. A classic example would be the coupling of guided-wave light to a discrete photodetector placed a few millimeters from the waveguide surface. This approach is attractive for a number of reasons. Firstly, the waveguide does not need to be cleaved and polished, as no end-faces are used in the coupling process. Secondly, making use of a slightly remote detector allows “pick-up” and place assembly components to be used in the manufacture of optics-hybrid circuits.

Optical interconnections using holographic optical elements minimize propagation delays; in addition, they reduce space requirements since several signals can propagate through the same network without mutual interference, many wiring patterns and high transmission rate. The optical signal can be divided to many output ports which are arrayed three-dimensionally and high densely by using forming function of wavefront with holograms. The holographic technology is expected to be applied for diffractive device of optical interconnection. Holographic technologies for optical interconnection devices have been studied actively[Yeh & Kostuk, 1995; Yeh & Kostuk, 1996]. Holography is the basis of many methods of optical data processing. Holograms are assigned important tasks in research on optical interconnections. Particular interest attaches to multifocus lenses for matrix processors and optical synchronization systems, and also to focusing devices that carry out prescribed transformations of wave fronts. By using various types of holograms, interconnections can be either fixed or variable. Dynamic holograms can make these interconnections dynamic; in addition, the method of wave-front reversal is the best physical basis for the development of associative two-dimensional memory. Holograms are also indispensable in one- and two- dimensional analog-digital converters [Honma et al., 2007].

In this section, we introduce some recently results of research about waveguide Holograms (WGH). Like any other type of hologram, they have their strong and weak points, but their compatibility with integrated-optics circuits is an advantage that allows us to regard them as promising. A WGH system is shown in Fig. 13, which is based on thin substrate waveguides bearing a hologram on the surface through which light is diffracted out. A light source is optically coupled to the waveguide such that light emitted from the source is caused to propagate along the waveguide, being diffracted out at intersections with the surface of the waveguide on which the hologram is formed.

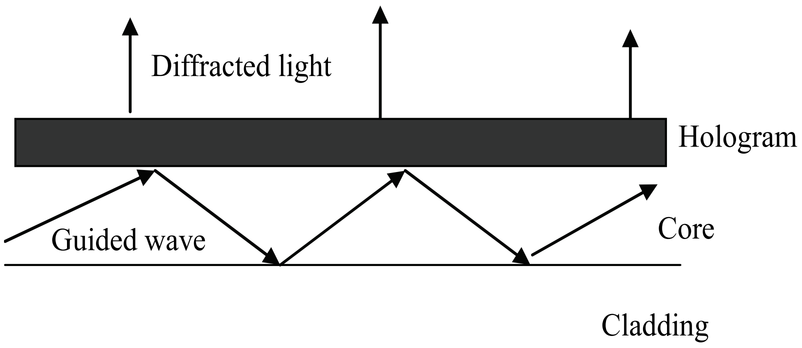


Fig. 13. Schematic of waveguide hologram system

Waveguide holograms have been used in many applications including filters, multiplexers, and DFB lasers. Since most of these applications require only one grating in the hologram, surface relief gratings become an appropriate choice. In the case of massive fanout optical holographic interconnects, many multiplexed and superimposed gratings must be recorded in the same hologram. Therefore, phase gratings are required for optical interconnect applications. Due to the nature of phase gratings, many-to-1 (fanin), 1-to-many (fanout), and many-to-many interconnects can be realized in both planar holograms and grating couplers. Another advantage of using phase gratings is that the strict phase matching condition of grating couplers can be alleviated (e.g., alignment requirements between laser diodes and grating couplers can be reduced) by either broadband processing of phase gratings" or multiple grating recording (i.e., each grating covers a particular angular acceptance).

3.2.1 Waveguide holograms of two-dimensional images and application in optical interconnects

Putilin discussed an optical interconnection employing waveguide and total internal reflection holograms as a basic element [Putilin, 1991]. It is shown that WGH have an extremely high efficiency, it forms high resolution and wide view image and permits to increase signal to noise ratio. WGH method permits to reconstruct two-dimensional images by one-dimensional waveguide mode because of distributed interaction between them. The efficiency of WGH depends upon length of grating and perturbation of refractive index of waveguide mode caused by WGH. So the performance efficiency of WGH can be up to 100% and all waveguide mode power will be used in image. WGH is situated one by one along the direction of waveguide mode propagation and can be reconstructed simultaneously as shown in Fig.14. The general efficiency of that WGH array is defined as (diffraction efficiency of each waveguide hologram-η)

$$A = 1-(1-\eta)^{n} \tag{8}$$

Where n is a number of WGH. For uniform n the brightness of images will decrease and some information (recorded on last waveguide hologram) will be lost. For uniform brightness of images WGH must be written with increasing efficiency:

$$\eta_{i+1} = \eta_i \,/\, (1+\eta_i) \tag{9}$$

Maximum efficiency is limited for concrete dynamics range of recording material and general efficiency will be defined as:

$$A = n\eta_{\max} \,/\, [1+(n-1)\eta_{\max}] \tag{10}$$

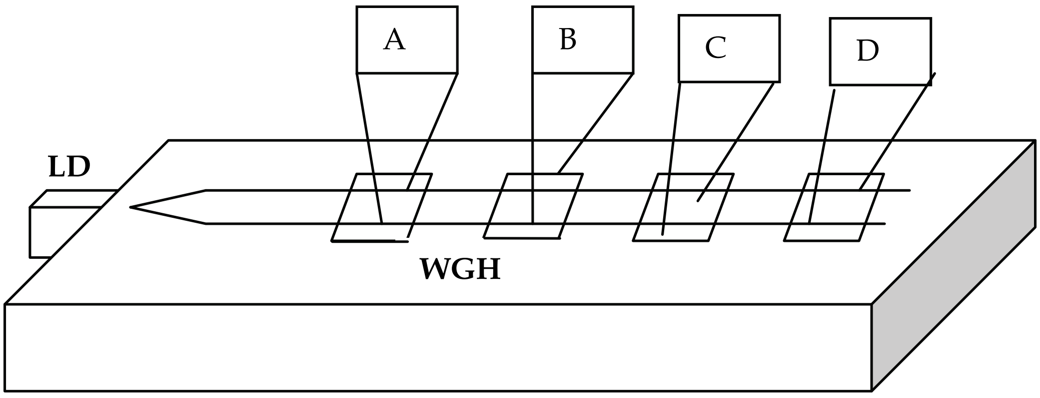


Fig. 14. Scheme of simultaneous waveguide hologram array reconstruction

The main demand of chip-to-chip interconnects is a very small distance between optical elements and image plane. Evidently requirements for chip-to-chip interconnection is similar to parameters of photolithographic equipment. WGH permit to obtain such characteristics. An application of WGH in chip-to-chip interconnection will be optimal because light can be separated from air-spaces completely. One of possible variants of that interconnection based on WGH of two-dimensional images is shown in Fig.15. The system works as explained in following steps: (1) Central WGH 1 transforms substrate waves from diode lasers to waveguide modes, (2) this light reconstructs information stored on WGH2. Each LD can reconstruct one line from WGH1 information if LD is arranged on VLSI in X direction , if LD array is arranged in Y direction then all lasers reconstruct one line from WGH1 information with individual shift in Y direction, so shape of reconstructed images from WGH2 will be changed. All variants of interconnect configurations must be recorded on WGHs. Modulation and additional reconfiguration of system can be done by integrated waveguide modulators situated between WGH1 and WGH2.

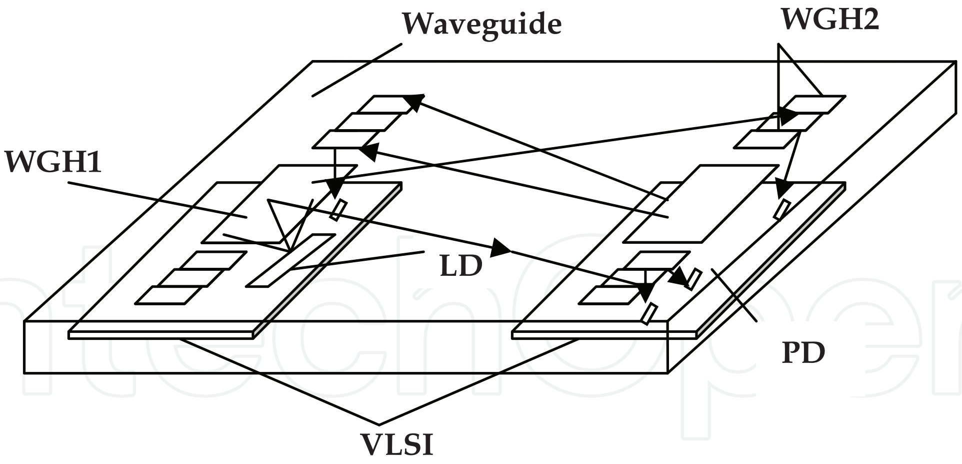


Fig. 15. The scheme of chip-to-chip interconnects based on WGH of two-dimensional images.

3.2.2 Optical multiplanar VLSI interconnects based on multiplexed waveguide holograms

Optical interconnects for very large scale integration systems based on planar waveguide holograms are analyzed in this section[Lin et al., 1990]. The combination of low loss waveguides and multiplexed waveguide holograms allows the construction of various compact planar architectures with high interconnect density and low insertion loss. The long interaction lengths possible in planar structures result in high angular and wavelength selectivity. Schematic diagram of a dual plane architecture of optical VLSI interconnects is shown in Fig. 16. One plane of the structure contains both electronic and optoelectronic elements (e.g., on a circuit board). Multiplexed holograms are fabricated in the other plane. It is also possible to achieve truly monolithic integration if a particular substrate, e.g., GaAs, is used to hold electronic, optoelectronic, and optical elements or if a mixed integration technique is used.

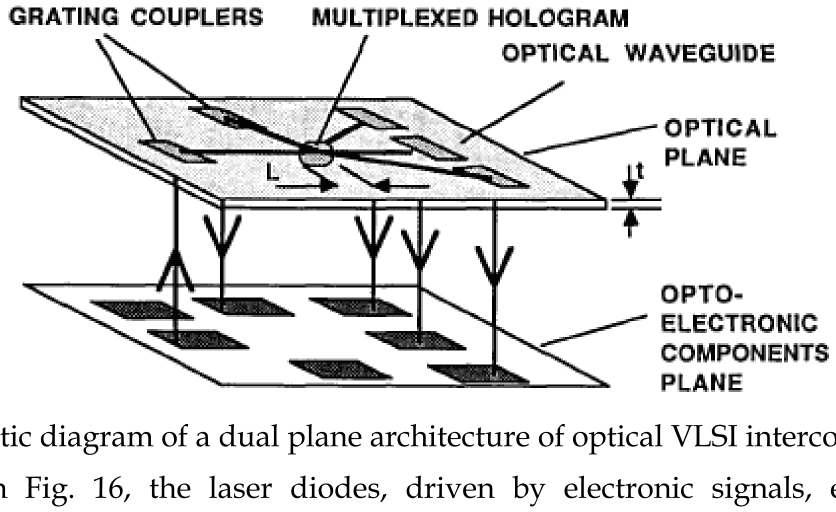


Fig. 16. Schematic diagram of a dual plane architecture of optical VLSI interconnects.

As depicted in Fig. 16, the laser diodes, driven by electronic signals, emit diverging wavefronts which can be transformed to guided waves by focusing grating couplers or a combination of microlenses and regular grating couplers. The guided waves are in turn redirected or distributed in various directions by multiplexed waveguide holograms. This configuration utilizes the advantages of holographic optical interconnects (high density, low loss) and yet allows for compact packaging achievable with integrated optics. It also has less stringent alignment requirements compared with conventional optics. Alignment is reduced to 2-D problems in the planar waveguide, since the vertical direction alignment is provided by grating couplers. The trade-off of this approach is that coupling of laser diodes to single-mode waveguides remains a difficult problem. Solutions, such as broadband or multiplexed grating couplers, are under investigation. In addition, these 2-D alignments can be solved by a computer-generated hologram approach in which grating couplers and planar holograms are written by an e-beam gun on the same substrate. Thus alignment problems/requirements between these holographic optical elements can be significantly reduced.

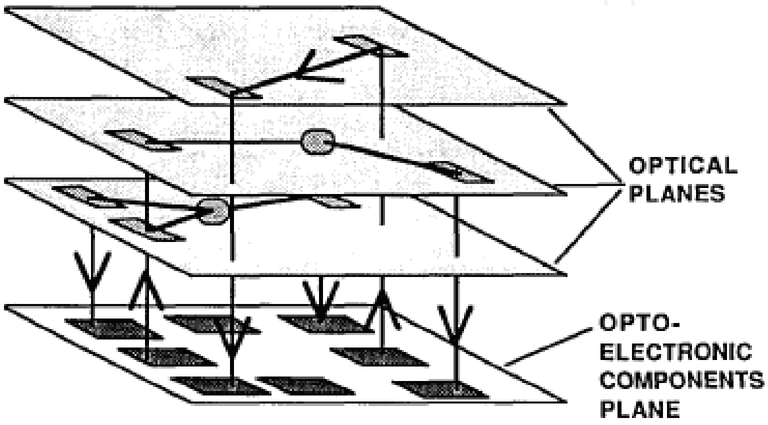
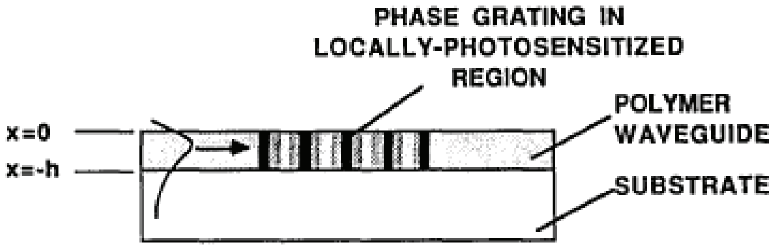
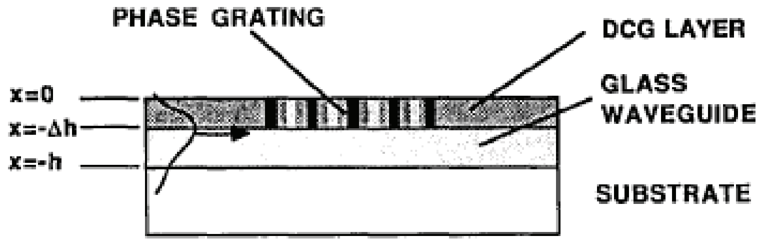


Fig. 17. Schematic diagram of a multiplanar interconnect architecture.



(a)



(b)

Fig. 18. (a) Planar hologram fully embedded in the waveguide; (b) Partially embedded waveguide hologram structure.

A multiplanar architecture, illustrated in Fig. 17. This multiplanar architecture preserves the advantages of a 3-D holographic optical interconnect system while simultaneously avoiding the drawbacks of bulk system layouts. It should be emphasized that since the typical waveguide and substrate thickness can be of the order of a few hundreds of micrometers in total, the thickness of the multiplanar system can still be of the order of centimeters, even for -100 layers.

To fabricate waveguides with embedded phase gratings, two material requirements must be fulfilled. Waveguides should have low loss and be photosensitive. If a low loss holographic material can be found, the grating may be recorded in the entire guided region (the fully embedded case illustrated in Fig.18(a)). Partially embedded waveguide hologram structure, illustrated in Fig. 18(b), is composed of a low loss ion-exchanged glass planar waveguide with a layer of dichromated gelatin (DCG) as the holographic material deposited on top of the regions where holograms are to be recorded. This structure gives satisfactory results for both grating couplers and planar holograms. To obtain the desired grating vector *K* parallel to the waveguide surface, the two recording beams interfering in the film must be separated by an angle $2\beta_r$ determined by:

$$\sin\beta_r = \frac{\lambda_r}{2d} = \frac{n_f \lambda_r (\sin\theta_G - \sin\beta)}{2\lambda} \tag{11}$$

where β is the input beam angular deviation from normal, θ_G is the guided wave angle, λr is recording wavelength. The system can realize reconfigurable interconnects (depending on incident wavelengths) and a total of a few hundred independent interconnect paths. However, multiple planar holograms fabricated in one plane can be stacked in a multiple plane system in which thousands, even tens of thousands of interconnects are obtainable. The maximum number of interconnects in one plane is limited by the channel angular width and grating coupler and detector sizes. The upper limit of the interconnect plane size is determined by the waveguide substrate size and waveguide quality. An additional trade-off arises between interconnectivity and system bandwidth requirements due to dispersion characteristics of the structure.

3.2.3 Use of waveguide holograms for input and transmission of infromation through a optical fiber

A waveguide hologram as well as any other kind of hologram makes it possible to form a structure of a light beam that matches the optical fiber employed for input, i.e., provides focusing and input of radiation into a fiber without any additional elements. The waveguide nature of the reconstruction process is an advantage of the waveguide hologram, which provides rapid reconstruction and almost equal amplitudes of waves reconstructed from different areas of the hologram when a short reading pulse is used and the diffraction efficiency is relatively low.

Dianov et al., presented a scheme for input and transmission of information on the complex amplitude transmittance of a one-dimensional transparency through a single-mode fiber communication channel with a waveguide hologram used for input [Dianov et al., 1996]. A schematic diagram of an optical setup with specially prepared waveguide holograms for input of information on the structure of a one-dimensional light field into a fiber communication line is shown in Fig. 19. In order to form a light beam of the required structure, the waveguide hologram is illuminated by a short radiation pulse in the form of a plane wave Ep(x, y, z, t) propagating along the x axis. The one-dimensional information to be transmitted is represented in the form of the complex amplitude transmittance t(x) of the one-dimensional transparency Tr, whose plane is practically aligned with that of the hologram. In certain cases, this information can be recorded on the hologram itself in addition to the structure that forms the radiation to be introduced into the optical fiber. To provide input of radiation modulated in accordance with the transmitted amplitude-phase information with the required spatial resolution into an optical communication line comprising a single-mode fiber, the waveguide hologram should focus radiation from each hologram element onto the fiber input, i.e., each hologram element should produce a converging spherical wave in the reconstruction process. The device interconnection level in reality is an optical fiber local area. The waveguide holograms just described may be integrated with optical fibers it will decrease number and complicacy of coupling elements.

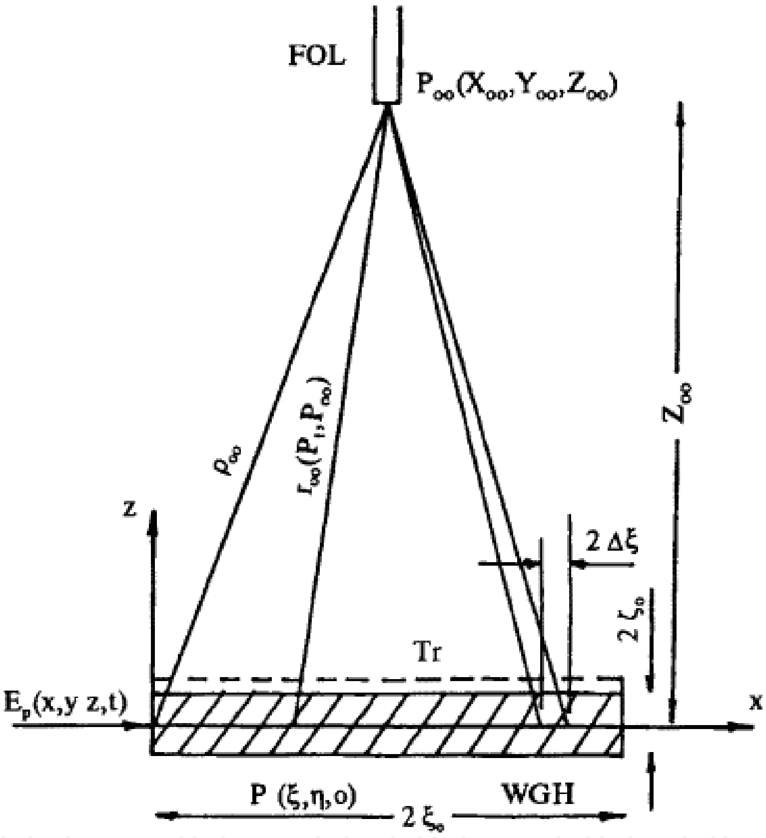


Fig. 19. Focusing of radiation into a fiber optics link by means of a waveguide hologram.

3.2.4 Waveguide coupling using holographic transmission gratings

Waveguide coupling using gratings has attracted considerable attention as an alternative to fibre butt-coupling, and a candidate for opto-hybrid integration of components. Sheard et al., studied on useing specially shaped gratings etched into the waveguide surface to couple light into the free space region above the waveguide [Sheard et al., 1997; Liao et al., 1998]. Figure 20 shows a waveguide core section with light travelling along the waveguide in the direction of the arrow on the left. The propagating light is progressively scattered by the etched grating and projects the light into the free space region above the waveguide surface. The parallelogramic shaped grating teeth are desirable, as this has been shown to be the most efficient structure for projecting the waveguide light into a single direction.

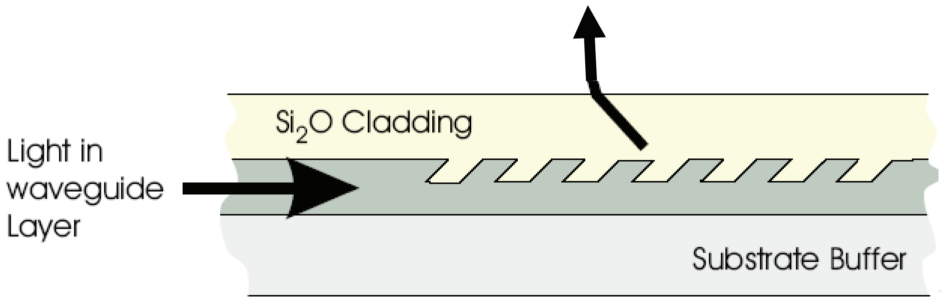


Fig. 20. Parallelogramic shaped etch grating for coupling light into the free space region above the waveguide

The intensity profile of the light coupled out of the waveguide surface can be varied by controlling the coupling efficiency. Either the grating depth can be varied along the length of the grating or the mark-to-space ratio of the grating can be varied as shown in Fig. 21 (a) and (b), respectively. Varying the mark-to-space ratio is easier using high resolution lithography. Varying the grating pitch and curving the grating lines by e-beam writing can be used to generate a focused beam from the output coupler or even an array of focussed points. A typical illustration of a focussing grating coupler is shown in Fig. 22. Here the light from a butt-coupled fibre is collected and focused by the grating a few millimetres above the waveguide surface. In most cases a diffraction limited spot size can be achieved.

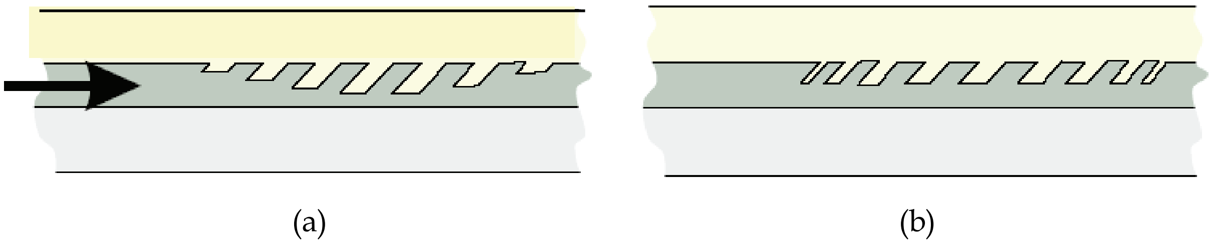

(a) (b)

Fig. 21. There are two simple ways to vary the intensity profile of the light coupled out of the waveguide surface, by controlling the coupling efficiency. (a) the grating depth along the length of the grating is varied, (b) the mark-to space ratio of the grating is varied.

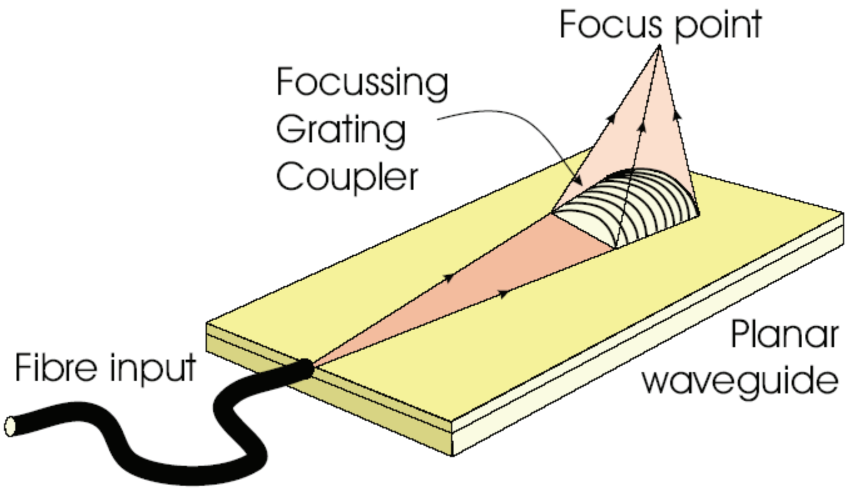


Fig. 22. Focusing grating coupler using a curved a chirped surface relief grating.

Because of its periodic nature, the grating perturbs the waveguide modes in the region underneath the grating, thus causing each one of them to have a set of spatial harmonics with z-direction propagation constants given by

$$\beta_v = \beta_0 + \frac{2v\pi}{\Lambda} \tag{12}$$

where v=0, ± 1, ± 2, . . . , and where Λ is the periodicity of the grating. The fundamental factor β_0 is approximately equal to the β_{m} of the particular mode in the waveguide region not covered by the grating. The principal advantage of the grating coupler is that, once fabricated, it is an integral part of the waveguide structure. Hence, its coupling efficiency remains constant and is not altered appreciably by vibration or ambient conditions.

4. The holographic waveguide for see-through planar display

The technology of see-through planar display (i.e. head-up display) is now used in the fields of military aviation, commercial aircraft, automobiles and other applications. A conventional see-through planar display system contains three primary components: a combiner, a projector unit, and a video-generating computer, so the size of the entire instrument is quite large, as shown in Fig. 23.

Because the holographic waveguide itself is transparent to the free-space light beams in the direction of perpendicular to waveguide, the observer can view the image produced by the hologram and at the same time can see through the hologram to view the scene at the opposite side of the hologram. This property is very useful for head-up display technology to eyewear display.

Fig. 23. A type of head-up display system.

In 2008, Sony Co. reported an eyeglass-shaped see-through display that can show full color video images, as shown in Fig. 24, and the holographic waveguide is the key component that realized the structure and display method in this sample. Fig. 25 illustrates this type structure of the holographic planar waveguide of the eyewear display [Mukawa et al., 2009]. The waveguide has an in-coupling and an out-coupling reflection volume hologram which have exactly the same fringe pattern and a mirror symmetrically positioned. Reflection volume holograms were employed because their diffraction bandwidths are much smaller than those of transmission holograms and could potentially enlarge the field of view of the eyewear displays. Each of these holograms has red, green, and blue hologram layers to transmit full-color images through the waveguide.

Fig. 24. A visitor wearing the prototype of eyeglass-shaped see-through display

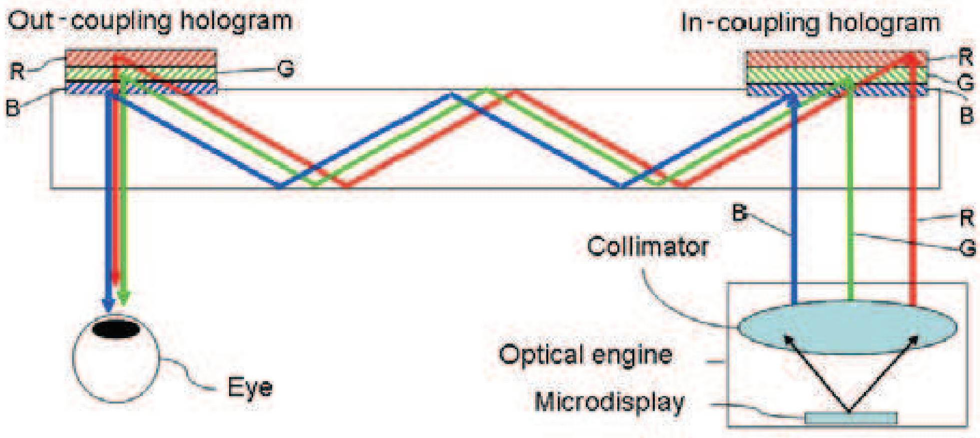


Fig. 25. The structure of holographic waveguide for eyewear display

5. Conclusion

The combination of hologram and optical waveguide is versatile technology that can be used in the optical data storage, optical connection, optical display and other applications. With the development of optoelectronic technology, we think that many new kinds of waveguide hologram devices will be invented and used widely in the future.

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Holography has recently become a field of much interest because of the many new applications implemented by various holographic techniques. This book is a collection of 22 excellent chapters written by various experts, and it covers various aspects of holography. The chapters of the book are organized in six sections, starting with theory, continuing with materials, techniques, applications as well as digital algorithms, and finally ending with non-optical holograms. The book contains recent outputs from researches belonging to different research groups worldwide, providing a rich diversity of approaches to the topic of holography.

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