Commercial aspects of diffractive optics

Lars R. Lindvold

OVC ApS, CAT Science Park, Frederiksborgvej 399, PO Box 30, DK4000 Roskilde, Denmark

lars.lindvold@ovc.dk

Abstract

The purpose of this article is to provide the reader with an up-to-date status on the commercial applications of diffractive optical elements. Rather than merely treating these as individual components, this article will also focus on the their applications from a systems point-of-view.

Diffractive optics – an introduction

Diffractive optics, as the name implies, are based on the principle of diffraction contrary to conventional optics that are based on refraction and reflection. This of course, also is reflected in the physical structure that determines the diffractive optical element. The common properties of such elements can be summarised as follows:

- A diffractive optical element consists of a periodic fringe pattern, typically with fringe spacing compatible with the wavelength of the light used. For visible light sources this figure would be in the range 0.5-2 µm.
- Depending on the application, recording material and the grating type, such structures will typically have a thickness between 0.1 and 100 µm.
- The function of the diffractive optical element is exclusively determined by the geometry and spatial variations in the width and depth of its fringe pattern.
- The periodic pattern is recorded as variations in the refractive index of the film and hence it is the phase of the light that is affected by the element.

Diffractive optics is a generical term and often this is replaced by a term that either describes the fabrication method or the way the fringe pattern is encoded. One of the terms used rather indiscriminately is that of holographic optical elements (HOEs). This term is only correct when the diffractive optics has been created by interferometrical means. Other frequently used terms are:

- Binary optics, for surface relief microstructures with square-wave profile.
- Digital optics or computer generated holograms (CGHs), for surface relief microstructures synthesised by a computer and created with high-resolution laser plotters or e-beam writers.
- Bragg gratings, for grating structures formed inside a film, e.g., photo polymers or dichromated gelatine (DCG). Also referred to as volume holograms.
- Lippmann gratings, special cases of Bragg gratings with the fringe pattern parallel to the surface like an interference filter.

The advantages of diffractive optical elements (DOEs) are their ability to generate arbitrary complex wavefronts from a piece of optical material that is essentially flat. A very powerful property is that of spatial and angular multiplexing found in volume phase holograms like dichromated gelatin (DCG) or photopolymers. On the other hand, the surface relief microstructures generated in photo resists lend themselves to mass production techniques like embossing and injection moulding.

In the case of surface relief structures, they may even be combined with liquid crystals to form electrically controlled diffractive optical elements. Two American companies are actively pursuing this area, viz. Digilens[1] and Meadowlark Optics.[2]

Diffraction gratings as components

Diffraction gratings, ruled as well as holographic, have been offered by a number of companies for the past 30 years and are regarded as an off-the-shelf component today. The major applications of these gratings are still as spectral dispersion elements in spectroscopic applications. More exotic applications include grating pairs for pulse compression and wavelength selectors on pulsed dye lasers.

The proliferation of ion-etching techniques has made it possible to "mill" diffraction gratings onto a number of optical materials covering the range from UV and VIS (quartz) to mid-IR (ZnSe, Si, Ge and GaAs). These gratings have been used for beam sampling or attenuation of high-power lasers. Companies offering these products for sale are Lasiris and Gentec both in Canada.

One of the key technologies in optical communication is dense wavelength demultiplexing (DWDM). The prerequisite for DWDM, among other things, is the fabrication of fibre Bragg gratings. The most widespread method for doing this is the use of phase masks. Phase masks are diffraction gratings made to diffract two equal 1st order beams with total suppression of the zero order beam.

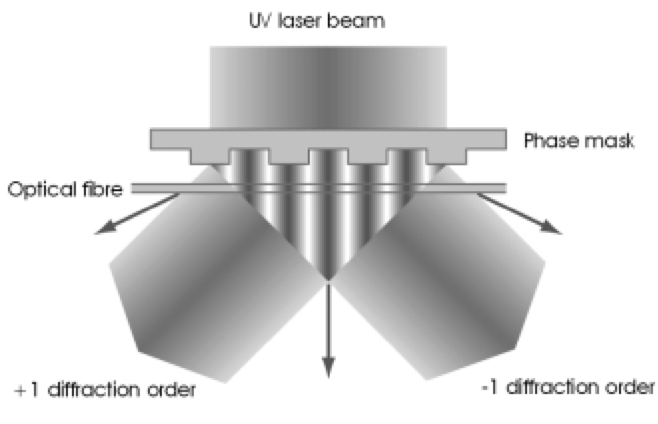

Fig. 1. Exposure scheme for formation of a Bragg grating inside an optical fibre. Drawing provided by ADC Denmark.

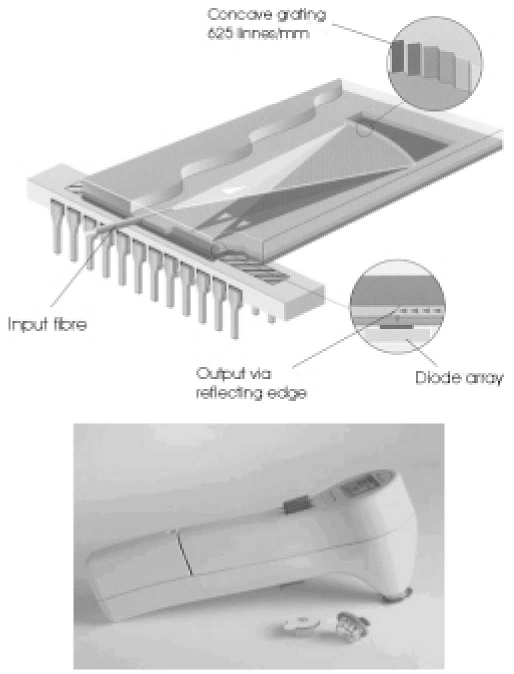

Fig.2. Monolithic miniature spectrometer and an example of its application. Top: Lay-out of monolithic spectrometer. Bottom: The BiliCheck™ from SpectRx.[6]

The gratings are made by holographic exposure of a photoresist coating on a quartz substrate. After proper development of the resist, the surface relief is transferred to the quartz substrate by reactive ion etching (RIE).

Illumination of the phase mask with an UV laser will generate two interfering beams as shown in Fig. 1. If an optical fibre is placed in close contact with the mask the inference pattern will expose the core of the fibre and form a Bragg grating.

The gratings for use with fibres typically have a period of 1000 nm, whereas those used in the fabrication of DFB semiconductor lasers have a period of 250 nm.

The two major suppliers of these masks are ADC Denmark,[3] formerly Ibsen Microstrucures, and Lasiris[4] from Canada.

Diffraction gratings in systems

Monochromators and spectrometers represent the most common and widespread systems using diffractive optics. It is characteristic that most of the major manufactures of spectrometers have an in-house production facility for holographic diffraction grating due to security of supply.

A very interesting trend in spectrometer systems has been towards miniaturisation. As shown in Fig. 2, this is done by monolithic integration of optical fibre, grating and diode array detector. One of the commercial applications of this device is a handheld point-of-care instrument for non-invasive diagnosing the level of bilirubin in babies suffering from neonatal jaundice. MicroParts GmbH[5] and University of Dortmund in Germany developed the spectrometer. The system is integrated in the point-of-care system and sold by US company SpectRx.

Other companies involved in production of miniature spectrometers are Zeiss and Jobin-Yvon.

SONY Precision Technology[7] in Japan has constructed a linear encoder, the Sony Laserscale™. The system is depicted in Fig. 3. A ruler made as a diffraction grating forms an interferometer with the polarising beamsplitter and the opposite right angle mirror. Moving the ruler in the interferometer results in a Doppler shift that is registered by the photodiode. By proper electronic processing this signal can be converted into a displacement of the ruler. The major advantage of the system is its insensitivity to wavelength drift in the laser diode, due to the double pass in the grating. A resolution of 0.03 µm can be achieved with this system. In order to minimise temperature effects, the grating has been etched into glass with a linear thermal expansion coefficient of -0.7×10^{-6} °C^{-1}.

Sony Precision Technology also manufactures an encoder with higher accuracy (0.01 µm) under the trade name Magnascale™. The encoder grating ranges from 10-370 mm in length.

Diffractive optics in security holograms

Most people are acquainted with optical verification devices (OVDs), like the sparkling holograms found on both credit cards as well as bank notes. The purpose of these OVDs is to authenticate the credit card or the bank note and to safeguard against counterfeiting. Optical verification devices are simple to verify visually and difficult to copy or counterfeit. This property is caused by the fact that OVD contains visible information as well

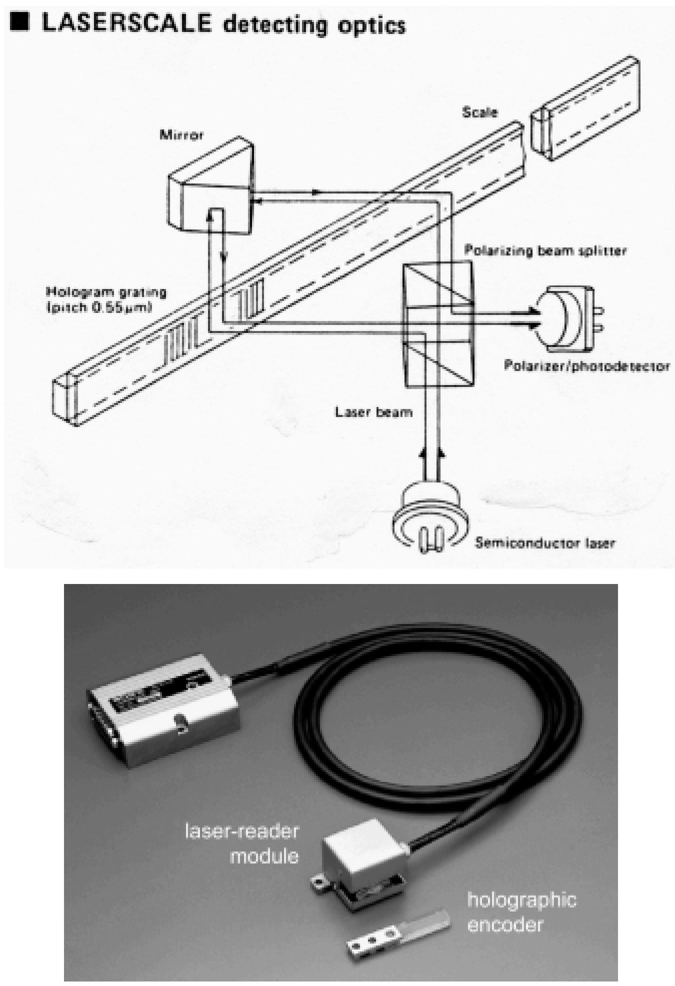

Fig.3. The optical layout of SONY Laserscale™ linear encoder.

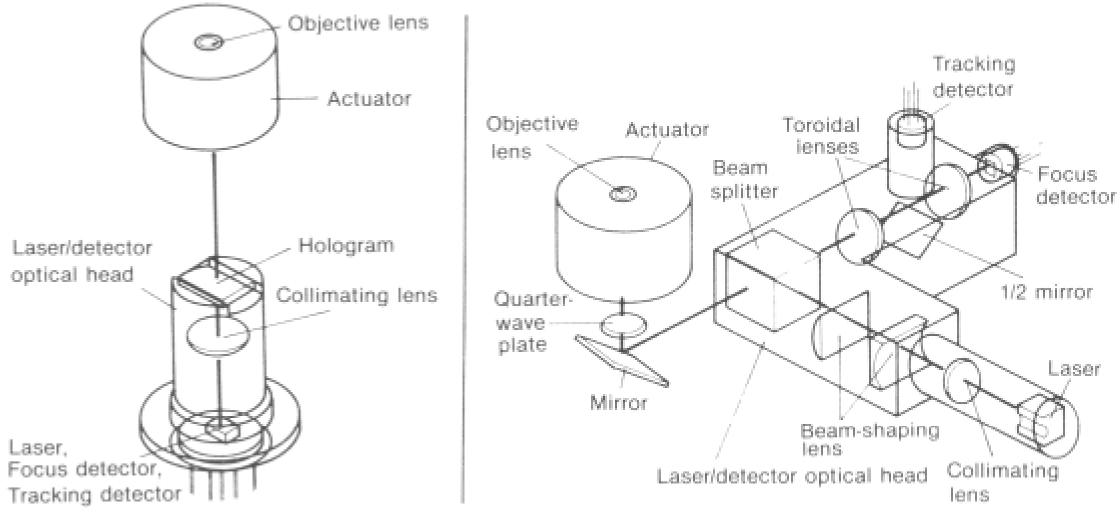

Fig. 4. The design of an optical pickup with HOE (left) and one using conventional optics (right). From Ref. 13.

as data readable only with special optical equipment. The latter effect is quite often achieved by the use of diffractive optical elements embedded in the image-containing hologram. One property that can be affected by the use of sub-micron structures is polarisation.

A full overview of all the optical methods available for OVDs is beyond the scope of this paper. R. L. van Renesse[8] gives an excellent review in the book “Optical document security”.

Fresnel zone plates for laser processing

A joint venture between Holo-Or[9] in Israel and Coherent Optics Division[10] in USA has launched a series of diffractive lenses to focus high power CO_2-lasers for materials processing. The advantage of using these lenses compared to usual plano-convecs and meniscus, are an improvement in spot size from 90-100 μm to 60 μm. Such a spot size can usually only be achieved with aspheric refractive lenses. This effect is achieved by forming a hybrid refractive/diffractive lens. Using reactive ion etching (RIE), a diffractive pattern emulating an aspheric addition, can be transferred onto the surface of a conventional plano-convecs lens in an infrared material like zinc selenide (ZnSe).

Another application of diffractive optics in this context is found in microsurgery with CO_2 lasers where it is necessary to use a visible red laser[11] for aiming. To maintain common focal point between the aiming laser and the CO_2-laser, a fine-pitched Fresnel zone plate is etched into the plano-convecs lens. As the grating structure is an order of magnitude smaller than the wavelength of the CO_2-laser (10.6 μm) it does not affects the optical properties of the refractive lens but only diffracts the visible laser light.

Optical pick-ups

The concept of using diffractive optics in laser pickups was originally suggested by W. H. Lee of Hoetron in USA, as a means to save weight and thereby increase the access time on the disc. For a comparison the “old” and new designs are shown in Fig. 4. As can be inferred from the drawings the concept is to replace bulky beamsplitting optics with a series of diffraction gratings integrated into one hologram. Such a step also involves a complete redesign of the optoelectronics; in this case the laser diode and the detectors.

The commercial suppliers of optical pickups incorporating diffractive optics for CD-ROM disc drives are Sharp and Toshiba. Particularly, Sharp[12] offers a widespread range of laser diode modules including diffractive optics.

With the introduction of the DVD disk, the Japanese electronics company Panasonic developed the bifocal laser pick-up based on a hybrid refractive-diffractive lens. This lens enables the optical pick-up to read from multiple layers simultaneously. The design of the lens is shown in Fig. 5.

The concept behind such a hybrid lens is making a Fresnel zone plate with a diffraction efficiency of about 40 %. This means that 60 % of the incoming light is not diffracted, this is referred to as the zero order. Light from the 0^{th} order can then be utilised by the refractive lens and the diffracted light will then act as a near addition to the refractive lens. In this way both bi- and tri-focal lenses can be designed. Typically, such hybrid lenses are manufactured by injection molulding.

Holographic scanners

Ever since IBM introduced their bar-code scanner (the IBM 3687), a lot of research has been done around the major computer and electronics companies of the world. The outcome so far, has been meagre compared to the substantial amount of publications available.

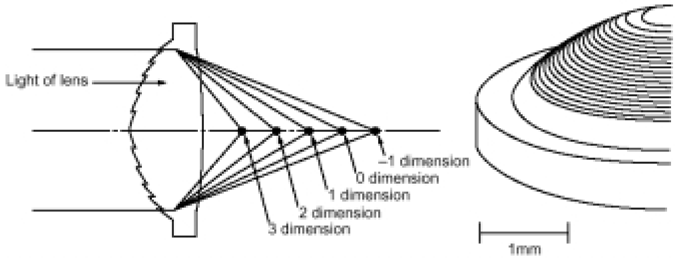

Fig. 5. Design of hybrid refractive-diffractive lens for use in Panasonic DVD players

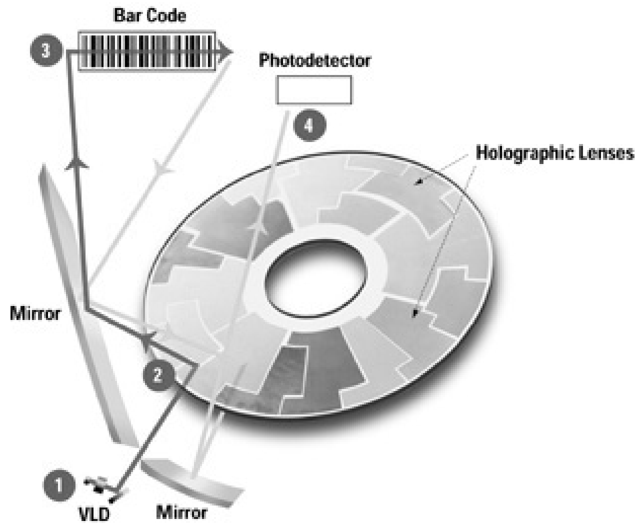

Fig.6. The layout of a Metrologic HoloTrack™ bar-code scanner with hologram, the VLD is a visible laser diode. Illustration can be found on their homepage.[14]

The drive for using holographic optical elements (HOEs) in graphic scanners and laser printers has mainly been the obvious savings in weight if a HOE could replace the bulky, and expensive, polygon mirrors. Today the market for HOEs is mainly in the barcode reader. Although both scan and focussing is handled by a holographic optical element as shown in Fig. 6 mirrors are used to fold the system in order to save space.

The only company ever to launch scanner systems for reprographic applications based on diffractive optics is a minor company Holotek in USA. This company was bought in 1996 by ECRM,[15] a company specialising in image setters.

Reduction of longitudinal chromatic aberrations in a telephoto lens

One of the outstanding properties of Fresnel zone plates is their strong negative chromatic dispersion, typically with an Abbe number of −3.5. The implication of this effect is that it can be used to correct for longitudinal chromatic aberration (LCA). In year 2000, Japanese camera manufacturer Canon introduced a 400 mm telephoto lens incorporating diffractive optics for correction of its LCA.[16] The savings in weight and length of the lens was quite significant. The weight of the lens went from 3.0 kg to 1.93 kg whereas the length was reduced from 317 mm to 233 mm.

Holographic projection screens

As mentioned earlier in this article one of the fundamental properties of holographic optical elements are their ability to generate arbitrary wavefronts. One particularly interesting high volume application is the so-called holographic diffusers. Originally this area was pioneered by Physical Optical Corporation[17] (POC) in the USA. Unlike conventional diffusing screens, the holographic diffusers were capable of generating lines or other geometrical shapes of diffused light. They could be used with lasers and incoherent light sources. Together with conventional gratings for dispersion of light these holographic diffusers are so widely use, that they are in the optics catalogue of Edmund Scientific.[18]

Another area where this component is used intensively is for illumination of liquid crystal displays (LCDs). Typical applications include Palm Pilots and mobile phones. Most of the holograms used in these applications are made on the OmniDex™ photopolymer developed and sold by DuPont Holographics.[19] Some of the holographic optical elements not only diffuse the light but also act as spectral filter.

One of the most recent developments in rear projection technology is the holographic rear projection screen. This screen is a volume phase hologram that makes is possible to view an image that essentially appears to float in the air. As the element only works at a narrow angle of incidence, due to Bragg diffraction, ambient light will not disturb the projected image. Furthermore, the screen will appear to be clear as glass when it is viewed out side the Bragg angle. At present displays with a diagonal size of 40 and 60 inches are commercially available from DNP[20] in Denmark and G+B pronova GmbH[21] in Germany.

Raman rejection filters

Although holographic interference filters have been commercially available in the form of head up displays (HUDs), only the manufactures of fighter planes seem to have had access to that component due to their high cost. A spin-off from that work has recently become accessible to a broader audience, viz., the holographic Raman rejection filters.

These are reflection filters of the notch type that will reflect between 99.99 % and 99.9999 % of the incoming light at a given wavelength with a bandwidth (FWHM) of ≈ 10 nm. The main impetus for this development has been the relatively low cost of the filter (1000 US$) that would make it possible to perform Raman spectroscopy using a single high quality monochromator and this filter. Usually Raman spectrometers have required a triple monochromator set-up to suppress the laser line.

At present one company, Kaiser Optical[22] in the US supplies most of the holographic Raman rejection filters in the world.

Head-up display

The use of head up displays (HUDs) in fighter planes has been an established technology for about 30 years now. Without going into details, a brief summary of the technological benefits of using HOEs in HUDs is compared to conventional HUDs:

- improvement in field of view,
- high reflectivity matched to the emission characteristics of the display unit,
- the possibility of incorporating some aberration correction in the element.

The leading manufactures of head-up displays are still Kaiser Optical (US), Pilkington Optronics[23] (UK) and OIP Sensor[24] (BE).

The HUDs are reflection HOEs made using the Denisyuk method, they act like reflection notch filters and under certain circumstances also as off-axis parabolic mirrors.

Recently, US car manufacturer Cadillac introduced HUDs in their DeVille series as an option combined with a night vision system.[25] The HUD is positioned at the windscreen in front of the driver.

Conclusion

The aim of this article has been to demonstrate that diffractive optics do have a great commercial potential. An important factor in achieving this goal is to appreciate the unique properties of diffractive optics rather than trying to re-engineer conventional refractive and reflective optical elements.

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About the author

Lars Lindvold holds a BSc in chemistry and a PhD from the Technical University of Denmark. For 15 years he held a position as senior scientist at the Optics and Fluid Dynamics Department at Risø National Laboratory. Main areas of work included materials for photolithography, fabrication of diffractive optics and biomedical applications of lasers. Last year, Lars Lindvold formed the company Optical Verification Components (OVC) ApS together with Jan Stensborg, manager of Stensborg ApS, Allan Mertner and Øresund Science Parks. The main activity in OVC is manufacturing of master holograms and inserts for use in injection moulding of pharmaceutical containers and medical disposables. Other activities include development of novel methods for mass fabrication based on UV technology. OVC is situated in the CAT Science Park.