

Diffractive optical elements for space communication terminals

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ABSTRACT

The potential of diffractive optical elements for advanced laser communication terminals has been investigated. Applications include beam shaping of high-power laser diode arrays, optical filter elements for position detection and hybrid (refractive/diffractive) elements. In addition, we present a design example of a miniaturized terminal including diffractive optics .

1. INTRODUCTION

Free space laser communication links with data rates between 10 Mb/s and 500 Mb/s are required to cover the large amount of communication needs between low orbit satellites, geostationary satellites and ground stations. The link distances range from 4000 km up to 73000 km. Optical communication is capable of very high data rates. Different designs have been investigated for various applications of laser communication terminals [1-3]. The optical systems are usually designed with refractive lenses and reflective mirrors. Modern microfabrication technologies enable the realization of planar diffractive optical elements (DOEs). By relying on diffraction and interference rather than on reflection and refraction, unique and novel properties can be realized complementing and exceeding the possibilities of traditional lenses, prisms, and mirrors. Contrary to earlier holographic elements recorded in materials like silver halide or dichromated gelatin, these elements can now be made of rigid materials, such as glass or fused silica. Thus producing optical elements that can survive in the harsh space environment for operating times of several years.

The objective of this work is to demonstrate the potential of diffractive optical elements (DOEs) for the design of optical and/or optoelectronic systems for advanced laser communication terminals. In the first part, we will review DOEs and its potential applications. In the second part, we will present a design example of a miniaturized terminal including DOEs.

2. DIFFRACTIVE OPTICAL ELEMENTS

2.1 Principle

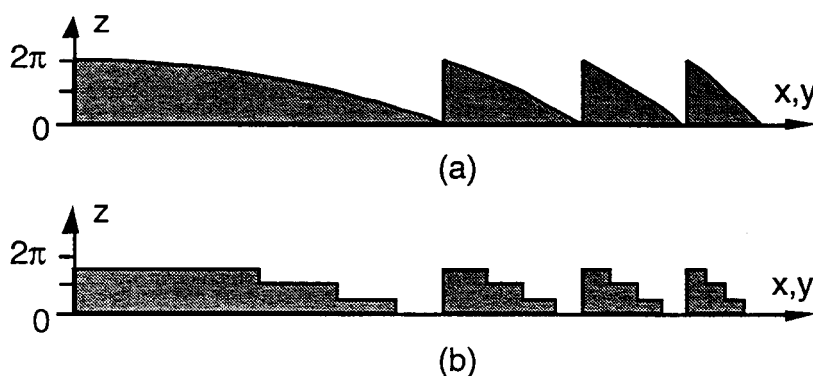


Fig. 1. Phase profiles for a phase Fresnel zone plate:
(a) continuous phase profile,
(b) 4-level phase profile.

Diffractive optical elements include holographic optical elements (HOEs) [4], computer-generated holograms (CGHs) [5], binary and multilevel surface-relief elements [6]. They are planar elements consisting of zones, which retard the incident wave by a modulation of the refractive index or by a modulation the

surface profile. The light emitted from the different zones interferes and forms the desired wavefront. The important performance characteristics of DOEs are the wavefront accuracy of the generated wave, the fraction of light in the desired wave (diffraction efficiency), and the straylight.

A well-known example is the phase Fresnel zone plate, also called micro-Fresnel lens, shown in Fig. 1(a). The phase profile can be generated as a smooth, continuous surface-relief element by e-beam [7] or by laser beam writing lithography [8]. In many cases the continuous phase profile is quantized into discrete phase levels, as shown in Fig. 1(b). Such a structure can be made by repeated etching steps. For 8 phase levels the theoretical diffraction efficiency is already 95%, i.e. close to the ideal continuous profile. The diffraction efficiency as a function of the number M of phase levels is given by (e.g. [6])

$$\eta = \left[\frac{\sin(\pi/M)}{(\pi/M)} \right]^2. \quad (1)$$

2.2 Manufacturing

Diffraction optical elements for space applications must comply with a number of requirements. The choice of suitable materials and processes are guided by the following requirements [9]:

- Stable long term optical and mechanical properties
- Good thermal stability
- Resistance to damage by cleaning operations
- Stability against damage due to ionizing radiation
- Low outgassing rates
- Good resistance to atomic oxygen for LEO applications

For the fabrication of diffractive optics, this leads to a preference for the following materials [9]:

- Optical glasses (Cerium stabilized glasses, glasses with high lead content)
- Dielectrics/Semiconductors (fused silica, sapphire, silicon, germanium, titanium oxide, magnesium oxide, silicon nitride, gallium arsenide, diamond)
- Metals like aluminum, copper, beryllium, gold, can be used for reflective elements.

Suitable techniques for realizing the microstructures in space qualified materials are based on a variety of high resolution lithographic and optical processes [6]. The typical procedure is to generate a mask by e-beam or by laser beam lithography. So as to achieve high efficiency, the mask is transformed into surface-relief structures by dry or wet etching. Using several masks, multiple profiles can be generated to improve the efficiency. Continuous-relief elements can be fabricated by direct writing of the DOE phase relief in photoresist by e-beam or laser beam. The developed photoresist relief can be transferred into glass or quartz by dry etching methods (ion beam milling, reactive ion etching).

3. POTENTIAL APPLICATIONS

Interesting aspects of DOEs are low weight, full design freedom, strong dispersion, and the possibility to make segmented elements, large arrays of elements, beam splitters, polarizers. These properties are useful for many applications of DOEs in space, including:

- Displays (head-up display, helmet displays)
- Image data processing (SAR image processing, filters)
- Spectroscopic applications
- Spectral filtering (wavelength multiplexing/demultiplexing, narrow bandpass filtering)
- Beam shaping (laser beam shaping)
- Imaging applications (IR systems, fiber couplers, micro-optical components)
- Integrated optoelectronic systems (smart sensors)

The strong dispersion is often considered as a drawback of DOEs. However, this is not critical for the present project, since the DOEs will be used with laser sources (semiconductor lasers, Nd:YAG lasers). On the other hand the dispersion is very useful for spectroscopic applications, because it depends linearly on the wavelength. Furthermore, the dispersion of DOEs is inverse in sign to the dispersion of refractive elements. Thus, achromatic elements can be realized by combining a refractive and a diffractive surface in one hybrid

element. In the following, we will briefly discuss some examples which are of interest for laser communications terminal.

3.1 Hybrid (refractive/diffractive) elements

The combination of refractive and diffractive surfaces, shown in Fig. 2, offers interesting new possibilities for optical design. The inverse dispersion of DOEs can be used to compensate the chromatic aberrations of refractive lenses. This enables the realization of hybrid achromats consisting of only one material. Hybrid achromats can be made thinner than conventional achromats, which can lead to higher transmission for UV and IR optics [9]. Hybrid elements can also be used to compensate the temperature variations, which have to be considered for space applications. For example, we have designed a hybrid achromat for a focal length $f = 8$ mm, a diameter $D = 5.2$ mm and a wavelength range $\lambda = 650 \pm 20$ nm (semiconductor laser). The numerical optimization has shown a wavefront error of 0.39λ for the whole spectrum in the center of the image plane. Additionally, the system, consisting of the lens, laser and housing, is insensitive to temperature variations in the range of -20° to $+40^\circ\text{C}$.

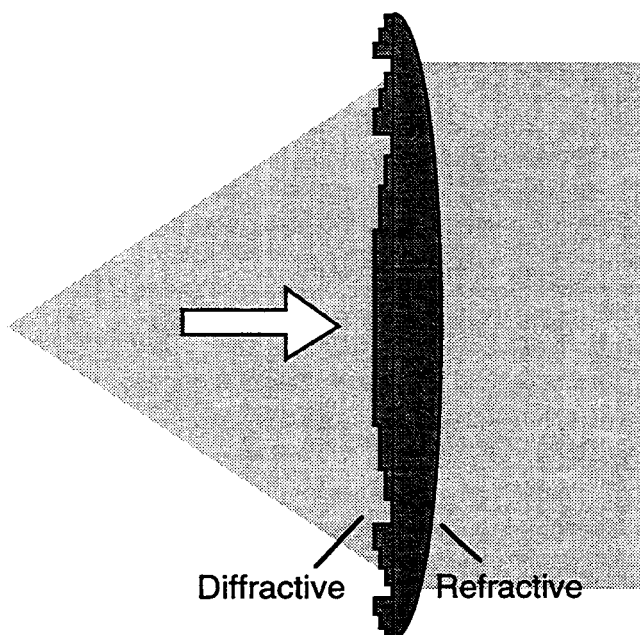


Fig. 2. Hybrid (refractive/diffractive) lens.

3.2 Beam shaping of high-power laser diode arrays

In the case of beam shaping, an input beam has to be converted into another beam with a different intensity profile. Typical applications are the conversion of a Gaussian beam into a uniform beam with rectangular shape and fan-out elements for array generation [10]. A very interesting application for space communications is the collimation of high-power laser diode arrays.

Fundamental mode beam quality can only be achieved by coherent beam shaping. The principle will be discussed in the following. In incoherent beam shaping, we cannot achieve a perfectly collimated beam. However, we can transform the emitting aperture of a linear diode array, which is very narrow ($\approx 1\mu\text{m}$) in one direction but can exceed 1 cm in the other direction, into a quasi-uniform two-dimensional distribution. Incoherent diode laser arrays are available with power levels of several Watts. These elements are of interest for the beacon where a relatively large area has to be scanned.

A compact demonstrator for coherent beam shaping has been built, which efficiently converts the double lobed far-field of a linear LDA, consisting of ten coupled emitters, into a single-lobed Gaussian mode of collimated light [11]. Two DOEs, a multilevel phase plate in the near-field of the array and a continuous surface relief-grating in the far-field, are needed for the conversion (Fig. 3). The theoretical efficiency of the set-up is 96.7%. On the realized breadboard, one third of the total emitted power was converted into a single Gaussian mode. The critical point in coherent beam shaping is the stability of the transversal mode

emitted by the LDA. Using a common external cavity, the stability and the modal separation of the LDA can be increased. This basic principle has been demonstrated for the coherent addition of three fiber lasers [12]. In this case, more than 72% of the output power has been coupled into a single collimated beam.

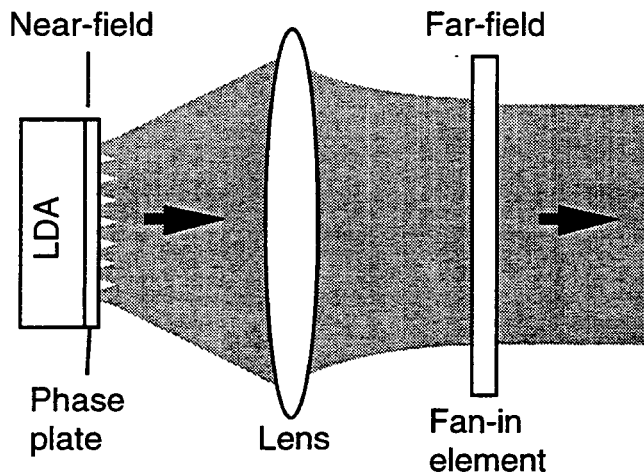


Fig. 3. Basic arrangement for far-field shaping.

3.3 Beamsplitters

A diffractive element is locally a grating that generates diffraction orders. Therefore a DOE is always also a beamsplitter, but in most cases only the first diffraction order is selected by the blaze or the Bragg-angle. By changing the blaze angle, the amount of light in the zero order can be increased, yielding an element which acts simultaneously as beamsplitter and focusing element. Fabrication problems occur for splitting angles near 90° , because feature size becomes then smaller than a micron.

The advantage of grating beamsplitters are their low weight and the possibility of multiple beamsplitting (one-to-many) [10]. A disadvantage (except for multiplexing) is the strong spectral dispersion.

3.4 Segmented elements for detectors

A big advantage of the fabrication methods for DOEs is the possibility to realize segmented elements. Within the same fabrication steps, a micro-Fresnel lens can be fabricated on the left side of the substrate and a beamsplitter (or another element) on the right side. Data can be submitted or received through the focusing element and the other element is then used for tracking and eventually autofocus control. Such systems are known from optical disk heads [13].

3.5 Polarizing elements, antireflective coatings

If the grating structure of DOEs is much smaller than the wavelength, the incident light cannot resolve the grating profile and is therefore not diffracted. Such a grating appears like a change in the refractive index depending on the grating profile. Analogous to thin films, it is possible to realize antireflection coatings by etching a fine grating into the surface of optical elements [14].

If the grating structure is in the order of the wavelength, only one of the two orthogonal polarizations may see the grating and the other not. These gratings are strongly polarizing, which enables the fabrication of polarizing beamsplitters or quarterwave plates [15].

Gratings in the sub-wavelength range are realistic for long wavelengths in the IR region. However, there are a number of techniques which have the potential to realize such elements also for the near IR and even for the visible (e-beam writing, X-ray lithography, interferometric recording).

4. DESIGN CONCEPT USING DIFFRACTIVE OPTICS

An interesting instrument for applications of DOEs is the monolithic mini optical terminal (MOMOT [16]) designed by Fisba Optik, see Fig. 4. This very compact terminal is mainly designed for shorter range applications of about 4100 kilometers and data rates of 12,5 Mbit/s. But with more powerful laser diodes,

which will become available soon, it will probably be usable for interorbit links of 45'000 km and at higher data rates as well.

Due to the small aperture diameter of 25 mm the diffraction angle is big enough that no point ahead assembly is required for pre-pointing the transmitted beam. The coelostat type pointing assembly is placed in front of the optics block and provides a hemispherical pointing capability. One of the mirrors is designed as a two axes fine pointing assembly. This philosophy simplifies the whole terminal very much, since no pupil imager is required for any internal scan elements. For transmitting and receiving, the total field is limited to the tracking area. Only the acquisition mode requires a field of approximately $\pm 1^\circ$.

The beacon is a self contained optical unit with its light supplied by an optical fiber and is mounted outside the pointing assembly.

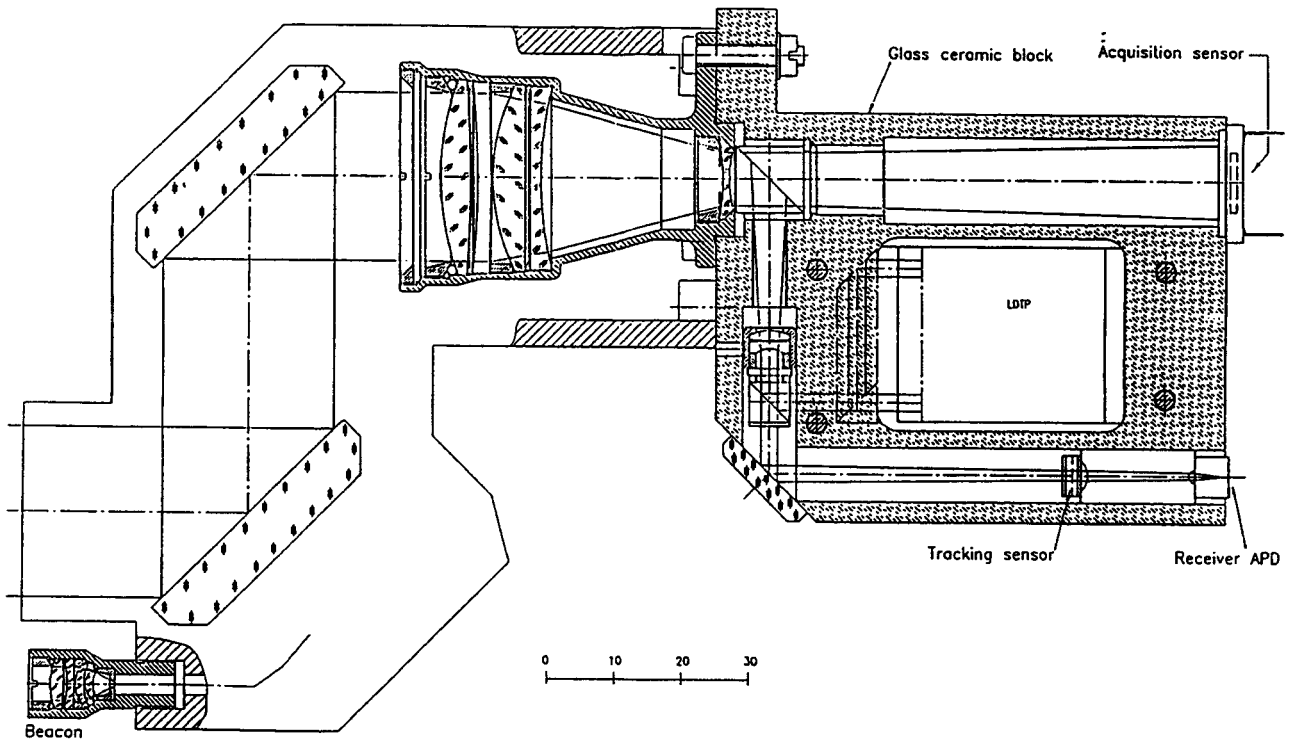


Fig. 4. Monolithic mini optical terminal.

The separately packaged redundant laser diode transmitter package supplies two collimated beams of 2 mm diameter each. The transmitter path has to deliver these beams and expand them to 25 mm diameter with a wavefront quality better than $\lambda/20$ RMS. The receiver has a field of view of $\pm 200 \mu\text{rad}$ and is combined with an integrated tracking sensor of $\pm 400 \mu\text{rad}$. The acquisition wavelength is 850 nm, the transmission wavelength is 810 nm. The components for the different functions are optically separated (or combined) by several beamsplitters, as shown in Fig. 4. The first beamsplitter transmits the long wavelength and the big field of view and reflects the short wavelength. The following components work on-axis only. The collimated 2 mm beam is separated by a polarizing beamsplitter into the transmit and receive path.

This small and complex optical unit contains a lot of optical components that might be replaced or combined with diffractive elements:

- the beacon collimator may be reduced from a 4 element to a 2 element design
- transmitter assembly can be diode arrays collimated by diffractive optics
- the complexity of the main objective may be reduced by a hybrid design
- the lenses in the monolithic tracking-receiver-assembly maybe diffractive
- the beam splitters – spectral or polarizing – may be realized by diffractive components

An important design concept for integrating diffractive optical elements is to use the new properties of these elements to either improve the performance or reliability of the whole system or to find a more economic solution. At the moment stray light is considered to be one important manufacturing problem. Therefore another design concept is to use not more than one diffractive element in an optical path. Therefore, it is planned to use diffractive optics for the following tasks:

- flattening the field of the acquisition sensor and maintaining the very compact size (Fig. 5)
- hybrid lens that creates the concentric ring pattern around the focus that is required for the combined tracking detector and receiver (Fig. 6)

The first element is part of the acquisition system. This system is used for detection of the counter terminal before the communication link can be established. The position is always known with an uncertainty of less than 0.4° . The acquisition optics is therefore specified to image a field of view of $\pm 0.96^\circ$ on a CCD array with 384×288 pixel of $23 \mu\text{m} \times 23 \mu\text{m}$ each. As the high aperture front lens group of the Galilei telescope is also used for this purpose, the layout results in an extreme telephoto lens with a focal length of 328 mm. This forms a very compact system but requires a strong negative group. During the design stage it was difficult to maintain a reasonably flat image for the total field. Considering the later application of reflective elements the design was modified to use a flat diffractive component. This flat element does not contribute to the Petzval sum and as a consequence the field curvature of the total system could be improved. The resulting system has a total length of 118 mm and provides a diffraction limited performance over the full field.

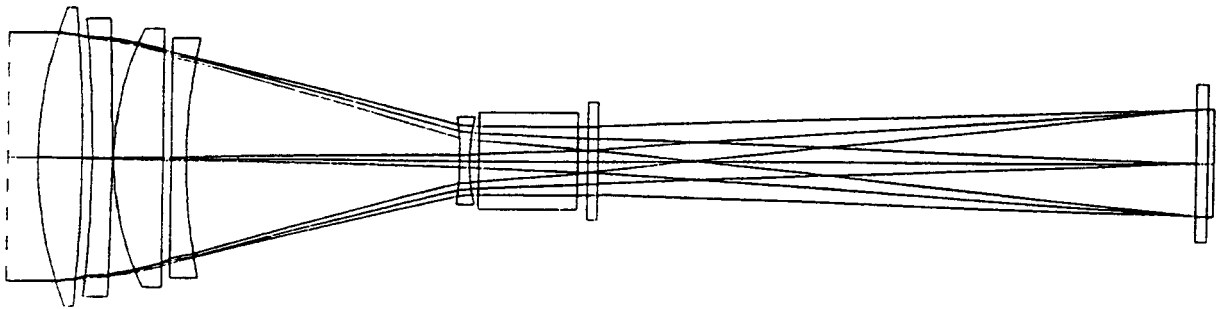


Fig. 5. Acquisition sensor including DOE for field flattening.

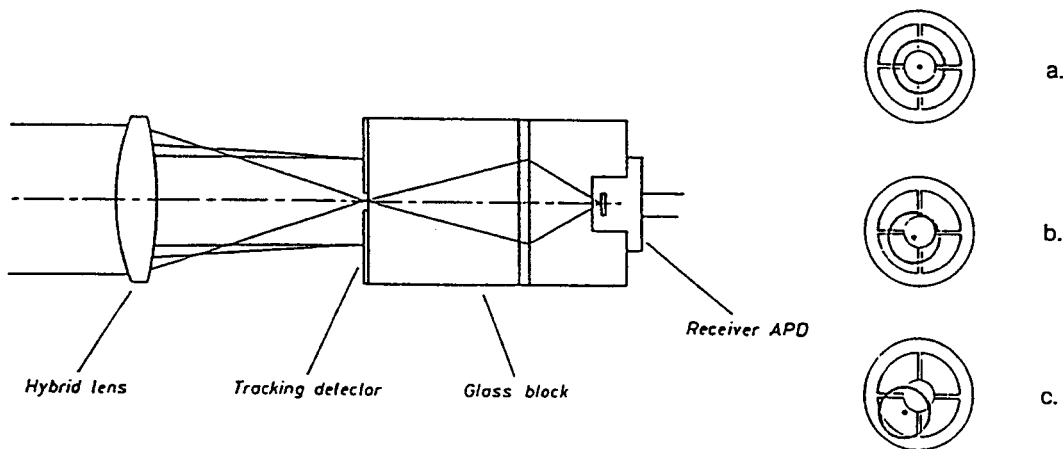


Fig. 6. Tracking detector and receiver.

The second hybrid lens is used in the combined tracking sensor / receiver system. To maintain a continuous communication link between two optical terminals, small deviations of the direction of the received beam should be continuously detected and compensated. Therefore, part of the received light is used to monitor the position of the transmitter and to produce a control signal for a beam stabilizer. A very reliable and compact design for a combined tracking sensor and receiver system consists of two key elements: the detector block has

the tracking detector at the front surface and the receiver APD at the back surface and contains the relay optics imaging the detectors on each other in a single compact piece of material (optical glass or fused silica). The tracking detector is a 4-quadrant detector with a hole in the middle to transmit the received light. This detector block is permanently aligned and mechanically and thermally stable. To produce the tracking signal a hybrid optics is used to form an image spot surrounded by a concentric ring. A small deviation of the direction results in a tracking signal from the asymmetry of the ring on the 4-quadrant detector without disturbing the receiver signal. With strong mispointing, the focus spot leaves the central aperture and illuminates one of the 4-quadrants. This results in a strong tracking error signal, that can be used to recover fast to a stable communications link. Usually, the small tracking errors will be compensated by the fine pointing assembly and the large errors by the course pointing assembly.

5. CONCLUSIONS

We have investigated the potential of diffractive optical elements (DOEs) for advanced laser communication terminals. The interest in DOEs for space applications is based on the flexibility to design almost any structure shape, the low weight, and the possibility to reduce the number of classical components. Contrary to earlier holographic elements recorded in materials like silver halide or dichromated gelatin, DOEs can now be made of rigid space qualified materials, such as glass or fused silica. They are useful for many tasks including beam shaping of high-power laser diode arrays, optical filter elements for position detection and hybrid (refractive/diffractive) elements. In addition, we have presented a design example of a miniaturized terminal including diffractive optics for two different tasks: i) flattening the field of the acquisition sensor while maintaining the very compact size, ii) a hybrid lens that creates the concentric ring pattern around the focus that is required for the combined tracking detector and receiver.

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