Planar-integrated free-space optics with high efficiency

J. Jahns

Planar-integrated free-space optical (PIFSO) systems have been in the center of the research at the ONT group for about 10 years. During that time, we could demonstrate the viability of this approach to build optical microsystems for applications in optical interconnection and sensing. An essential step towards practicality is now being taken, namely, the design and fabrication of systems with high efficiency.

Conventional lithographic fabrication has been used until recently to implement the optical elements as DOEs (diffractive optical elements). This approach offers very high design flexibility, but it is limited with regard to the achievable efficiency in such cases where large deflection angles are required. As a result, the DOE technology has allowed us to implement a variety of systems demonstrators. In order to make the PIFSO concept useful for real-world applications, we are now investigating suitable fabrication technologies that allow one to implement the elements as ROEs (reflective or refractive optical elements). The following approaches are being investigated:

- Gray-scale lithography using HEBS (high-energy beam-sensitive) glass technology, see, e.g., [1]: in collaboration with the University of Jena and the Fraunhofer-Institute IOF in Jena this technology, which combines direct e-beam writing and replication, is being demonstrated for the first time at systems level. First results are presented in two papers in this Annual Report by R. Heming et al.. An alternative approach to the HEBS mask technique is described by M. Gruber et al. where in collaboration with a group from UCSD a carbon-based film (LAF) is used [2].

- Half-tone printing and analog photoresist development: binary masks using pulse-width modulation are used to encode the phase information of an optical element [3]. Smooth profiles can be realized by a low-pass filtering step in the fabrication procedure. The approach is currently being developed in a diploma thesis at ONT.

- Single-point diamond turning for microoptics [4]: in a collaboration with colleagues from the National Chiao Tung University, Taiwan, we use this conventional approach to demonstrate a systems design that is based on circularly symmetric elements. A first demonstrator has just been completed and will be tested during the next couple of months.

- Finally, an interesting approach for fabricating arbitrary phase profiles is the use of ultra-precision micromachining. The feasibility of this approach to fabricate deep-high quality phase profiles has been demonstrated, for example, in [5]. Efforts for using that technology for PIFSO systems will be undertaken in the near future.

As stated above, the main purpose of following the different alternatives is the need to build highly efficient systems. Currently, with the DOE technology, typical insertion losses for a system range between 5–10 dB. Using the fabrication techniques described above to make reflective/refractive systems, it will be possible to reduce the insertion loss of less than 3dB (also assuming high-quality mirrors). Besides the improvements in efficiency, the potential for mass replication at the systems level is another important goal.

Designing a 3-D optical multilayer due to merging the concepts of stacked and planar-integrated free-space optics

M. Jarczynski, J. Jahns

Optical interconnects aim to overcome the communication bottleneck of electronic computers based on their large bandwidth, low latency and the use of the third dimension [1]. For the optical implementation of 3-D setups suitable microoptics approaches are required. Two suitable approaches have been investigated extensively: stacked microoptics [2] and planar-integrated free-space optics (PIFSO) [3]. For stacked microoptics several planar substrates (containing arrays of lenses, prisms etc.) are stacked together as it is illustrated in the left top part of Fig. 1. It is excellent appropriated for on-axis optical interconnects with passive components, e.g., fiber interconnects with gradient-index optical elements. The main challenge of this concept lies in the assembly of a large number of substrates with high accuracy and fidelity.

PIFSO is based on folding the 3-D optical setup into a 2-D layout, where the optical elements are placed on both main surfaces of a planar substrate (top right part of Fig. 1). Along the axis of propagation the signals are accessible at every surface for miscellaneous interaction with passive or active optical or electronic elements. For the processing standard methods like lithography and etching, injection molding, casting or embossing as well as bonding are suitable. The 2-D layout of the optical elements makes the fabrication of the optics easy using planar mass fabrication techniques (lithography, replication), however, it also imposes constraints on the geometry of the optical systems. In order to achieve more design freedom, we consider the possibility of merging stacked optics and PIFSO. The result is a 3-D optical multi-layer as shown in the bottom part of Fig. 1. The possibilities are exemplified by means of the above used optics with an extension on out-coupling at the same lateral positions but on opposite sides and on an inside placed beam splitter and mirror. Additional design freedom occurs for both, the system and the individual components by the possibility to split an optical function between two consecutive surfaces. Currently, we are implementing a 3-D optical multi-layer system in an interface prototype for an optical CPU-MEM-interconnect in the EU-funded HOLMS project (Fig. 1 right).

Fig. 1: Schematic to point up the merging of stacked optics and PIFSO; a design for an interface application.


Experimental specification of a P2P-interconnect for a CPU-MEM-bus

M. Jarczynski, T. Seiler, R. Heming, M. Gruber, J. Jahns

In the previous article of this annual report a P2P-interconnect was analyzed theoretically with respect to the tolerance of the transmitter misalignment (see also [1]). Here, we present experimental results for the fabricated PIFSO-module where the efficiency and crosstalk were analyzed. For the experiments the setup shown in Fig. 1 was used.

Fig. 1: left: Flow-chart of test setup. right: Experimental setup in the laboratory.

A quantitative characterization of the interconnection is accomplished by the use of a MT-terminated single-mode fibre-bundle and a stand-alone multi-mode fibre as a transmitter and a receiver, respectively. The measurement setup is calibrated by the use of butt-coupling of the transmitter and the receiver fibre. The insertion of the optical module yields to the measurement of its optical efficiency. The crosstalk is measured by shifting the transmitter fibre to the next channel while the receiver fiber is still held at its position. The results of the channel efficiency and crosstalk are presented in Fig. 2. The diagram shows that the crosstalk suppression is $-30$ dB or better, which is sufficient for our purpose.

Theoretical calculations have shown that the maximum feasible efficiency for this module is $\eta_{\text{theor}} = -5.5$ dB. Fig. 2 shows that the measured efficiency is only appr. $-8.5$ dB, hence worse than expected. An analysis of the quality of the multi-level diffractive elements has shown that an improvement will be possible.

Fig. 2: A list of acquired data for the efficiency and signal-to-noise ratio.

Tolerance analysis of a P2P-interconnect for a CPU-MEM-bus

M. Jarczynski, J. Jahns

In a previous annual report [1] a P2P-interconnect implemented in planar-integrated free-space optics (PIFSO) technology for an optical interface in a CPU-MEM-bus was presented. There, a specific optical design was used based on "hybrid imaging". For the optics of this module a tolerance analysis is performed which considers lateral and longitudinal displacement of the transmitter (Fig. 1). The analysis is based on a ray tracing-simulation using a tool that was specially developed for PIFSO systems [2].

Misalignment occurs due to the bonding process of laser-diode chips on a multi-chip module (glass substrates) and due to its assembly with the PIFSO substrate. The design has to be checked on its tolerance to the misalignment described above. For the worst case of transmitter misalignment in x, y and z less than ±10µm is specified. The tolerance analysis is accomplished by simulating several cases of displacement that are shown in the left picture of Fig. 1.

The diagram of Fig. 1 shows the result of the tolerance analysis. The percentage of rays gathered in the destination area and the N.A. of the out-coupled beam are presented for several displacements of the transmitter. The first column shows that ray loss is absent, if the transmitter is optimal aligned. The next eight columns result that a maximum of 27 % of the rays are lost in the tolerance regime of ±10µm. Assuming that each ray carries an equal amount of optical power, the power loss of this design is approx. 1.25 dB in the worst case. Adding this value to the diffraction and Fresnel losses of the DOE's (η_{theor} = -5.5 dB) the worst case scenario achieves losses of around 6.75 dB. Losses by a mismatch of the N.A. of the detector or waveguide are not relevant, because the critical waveguide N.A. of 0.2 is not achieved.

In order to keep the loss due to misalignment to less than 6% the tolerances must not exceed ±5µm in the lateral and longitudinal direction (last eight columns). The worst case is than limited to 5.76 dB loss.

![Fig. 1: The schematic clarifies the transmitter displacement and the diagram shows the results of the simulation: the percentage of rays gathered in the destination area and the N.A. of the out-coupled beam are presented for different positions of the transmitter (misalignment).](image)


Fractional Montgomery effect
A. W. Lohmann*, H. Knuppertz, J. Jahns

*Universität Erlangen-Nürnberg, Lehrstuhl für Nachrichtentechnik, Cauerstr. 7, 91058 Erlangen

Montgomery and the related Talbot effect deal with the longitudinal periodicity of wave fields. For periodic objects the Talbot effect describes the replication of the initial wave field in certain distances. The Talbot distance is given by 

\[ z_T = \frac{2}{(\nu_1^2 \lambda)} \]

with \( \nu_1 \) the first harmonic spatial frequency of the diffracted field and \( \lambda \) the wavelength. We have demonstrated earlier that a field replication in propagation direction not only occurs for periodic objects like in the Talbot case but for a much greater class of objects [1]. For every object that suffices the Montgomery condition self-imaging occurs. The Montgomery condition \( \nu_m^2 = \frac{1}{\lambda^2} - \left( \frac{m}{z_T} \right)^2 \) selects frequencies in the spatial spectrum that follow the linear integer index \( m = 1, 2, 3, 4, \ldots \), Talbot objects follow a quadratic subset. Thus a harmonic analysis of Talbot (eq. 1) and Montgomery objects (eq. 2) indicates an obvious kinship.

\[
U_T(x, z) = A_0 + \sum_{m \neq 0} A_m \exp \left[ 2\pi i \left( m\nu_0 x - m^2 \frac{z}{z_T} \right) \right] 
\]

\[
U_M(x, z) = B_0 + \sum_{m \neq 0} B_m \exp \left\{ 2\pi i \left( \frac{m}{\sqrt{|m|}} \nu_0 x - |m| \frac{z}{z_T} \right) \right\}
\]

Both fields are replicated at the self-imaging distance \( z_T \) when the second part of the argument in the parenthesis becomes an integer. Furthermore, Talbot objects create at fractional planes with, e.g., \( z/z_T = 1/2, 1/3, 1/4, \ldots \), field distributions that resemble strongly the initial one.

Here we investigate the same property for the more comprehensive family of Montgomery objects [2]. Indeed, with specific sets of the coefficients \( B_m \) lateral non-periodic Montgomery objects feature field distributions at fractional planes that resembles the initial distribution like Talbot objects do. This behavior shall be demonstrated with equal sets of coefficients \( B_m = A_m = \text{sinc}(m/2) \). The field distribution in the Talbot case can be generated with a Ronchi grating (fig.1a), in the Montgomery case it is a non-periodic object (fig.1b).

At half the self-imaging distance in both cases we see a contrast reversal, the intensity pattern is just a mirrored sample of the initial distribution. Other suitable sets of coefficients indicate the same behaviour. Thus it is justified to introduce the term “fractional Montgomery effect”.


Simulation of a multimode waveguide as a Montgomery interferometer

H. Knuppertz, J. Jahns

Like any interferometer, the Montgomery interferometer is capable to serve as an optical temporal filter device [1]. A Montgomery interferometer is based on the self-imaging effect. It consists of two diffracting masks separated by a multiple $N \cdot z_M$ of the self-imaging distance. A time delay occurs due to the different path lengths for the different diffraction orders. The characteristic time constant is $\tau = N \cdot \lambda/c$. We want to use the Montgomery interferometer in the Terahertz region ($\approx 10^{12}$ Hz) for information processing in high-speed optical networks. For this purpose, delay times $\tau \approx 0.1 \ldots 1$ ps are required and hence the length of the interferometer has to be quite large, since $L = N \cdot z_M$. For example, a delay of $\tau = 0.05$ ps arises for a wavelength of $\lambda = 1.5 \mu$m if $N = 10$ longitudinal periods are used. For a self-imaging distance assumed to be $z_M = 1.5$ cm a total length of $L = 15$ cm would result. In order to avoid vignetting, a waveguide-optical implementation is of interest as demonstrated earlier for Talbot interferometers [2]. Such “multimode interference devices” can be implemented as low-loss stripe waveguides using, for example, silica-on-silicon technology. Here, we simulate the propagation of a Montgomery wavefield in a multimode waveguide device. The wavefield consists of discrete modes that obey the Montgomery condition for the paraxial case: $\nu_{x,m} \approx \sqrt{m\nu_1}$ with $n = 1, 2 \ldots M$. In the simulation we used $M = 3$ modes. They are generated by a diffractive optical element assumed to be positioned at $z = 0$ (fig.1). The initial distribution is replicated at integer multiples of the self-imaging distance. At fractional planes $z = (n+1/2)z_M$ the identical amplitude distribution occurs but with the opposite phase [3].

Fig. 1: Simulated propagation of a Montgomery wave field in a planar multimode waveguide. Different scales are used for both axes. The physical dimensions assumed for the waveguide are 150 mm in length and 0.18 mm in width. The plot shows the amplitude distribution over a length of ten periods in the longitudinal direction.

For the simulation, an ideal match between the modal patterns of the Montgomery wavefield and of the waveguide was assumed. In general, however, the modes do not match exactly. Considerations on the design of a waveguide implementation of the Montgomery interferometer are currently ongoing.


Necessary condition for the self-imaging of spatially incoherent wavefields

J. Jahns and A. W. Lohmann*

*Universität Erlangen-Nürnberg, Lehrstuhl für Nachrichtentechnik, Cauerstr. 7, 91058 Erlangen

The self-imaging of a coherent wavefield has been widely studied for more than a century. Well-known is the Talbot effect [1] that occurs when a periodic object \( u(x) \) of period \( p \) is illuminated by a plane wave of wavelength \( \lambda \). Then, at regular distances behind the object the amplitude of the propagating wavefield is identical to the amplitude of the object (in the paraxial case). The longitudinal period of the wavefield, known as the Talbot distance, is given as \( z_T = \frac{2p^2}{\lambda} \). Using a 1-D notation for simplicity and the index denoting the \( z \)-coordinate, this can be formulated mathematically as

\[
\text{if } u_0(x) = u_0(x+p) \implies u_z(x) = u_{z+z_T}(x) \tag{1}
\]

For the spatial frequencies the following relationship holds: \( \nu^2_{x,m} = \frac{1}{\lambda} - \left(\frac{m}{z_T}\right)^2 \). Eq. 1 states that the lateral periodicity of a wavefield is a sufficient condition for the longitudinal periodicity in \( z \)-direction. The necessary condition for the \( z \)-periodicity was given by W. D. Montgomery [2]: in that case, the Fourier transform must consist only of discrete spatial frequencies \( \nu_x \) with \( \nu^2_{x,m} = \frac{1}{\lambda} - \left(\frac{m}{z_T}\right)^2 \) where \( m = 0, 1, 2, \ldots, m_{\text{max}} \):

\[
\text{if } u_z(x) = u_{z+z_T}(x) \implies u_0(x) = \sum_m A_m \exp(2\pi i \nu_{x,m} x) \tag{2}
\]

Self-imaging also occurs for (spatially) partially coherent wavefields, known as the Lau effect [3, 4]. It is convenient to describe partially coherent (monochromatic) wavefields by the mutual intensity, here denoted as \( J_{x_1,x_2}(z_1, z_2) = \langle u_{z_1}(x_1) u^*_z(x_2) \rangle \) where the brackets indicate the time average [5]. We consider the case where \( z_1 = z_2 = z \). Like the complex amplitude \( u_z(x) \), the mutual intensity \( J_z(\xi) \) obeys the Helmholtz equation (with \( \xi = x_1 - x_2 \)) [5, 6]. Hence, one can show that similarly to the situation of coherent wavefields, one can formulate sufficient and necessary conditions for the longitudinal periodicity of \( J_z(\xi) \):

\[
\text{if } J_0(\xi) = J_0(\xi+p) \implies J_z(\xi) = J_{z+z_T}(\xi) \tag{3}
\]

and

\[
\text{if } J_z(\xi) = J_{z+z_T}(\xi) \implies J_0(\xi) = \sum_n B_n \exp(2\pi i \nu_{x,n} \xi) \tag{4}
\]

Note, that this expression is identical to the one in eq. 2, however, the condition is now expressed in terms of the mutual intensity. Consequently, the design of suitable objects is different for the coherent and for the partially coherent case.

[1] H. F. Talbot, Phil. Mag. 9 (1836) 401
Apodized multilevel diffractive lenses

Q. Cao and J. Jahns

Focusing and imaging are everlasting topics in optical science and optical engineering. In the visible spectral region, the focusing can be realized by refractive lenses and/or multilevel diffractive lenses. And in the spectral regions of soft x-rays and extreme ultraviolet radiation, the focusing can be implemented by photon sieves [1, 2, 3] and/or various Fresnel zone plates [4, 5]. Recently [5], we established a theory for general modified Fresnel zone plates by introducing the equivalent aperture (or pupil) function. Based on this theory, one can properly choose the positions and radii of those open rings to construct a desired diffraction-limited focal spot shape.

By using Babinet’s principle and the concept of complex conjugate sub-zones (CCSZs), we here extend the above theory [5] to multilevel diffractive lenses.

The CCSZs for 4 phase levels are shown above. By adjusting the parameter $\alpha$, one can obtain desired equivalent pupil function value at certain position. Accordingly, one can control the focal spot shape. The key point is that, except for the different etching depths, the structure are symmetric about the points $C_{\alpha}$. For higher-level case, one can simply extend the structure. We numerically designed an 8-phase-level diffractive lens to generate a desired Gaussian focal spot. The simulated result is shown below. One can see that the calculated intensity distribution (solid curve) is in good agreement with the desired Gaussian focal spot shape (dashed curve).

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Fiber-to-the-home is an important area of optical communication. It can greatly increase the communication capability of an individual family. Normally, one single-mode fiber can carry two different communication wavelengths, one is 1.31 µm and the other is 1.55 µm. These two different wavelengths are often designed to be propagated at two opposite directions. In this case, one needs a component to simultaneously implement the functions of separation, output coupling, and input coupling, for the two oppositely propagating wavelengths.

Here, we consider the use of a diffractive lens as the key component. It is well known that diffractive optical elements have large chromatic dispersion. This property can be used to separate the two different wavelengths to two different positions in space. Our task is schematically shown below. The 1.31 µm wavelength emitted from the VCSEL needs to be coupled into the fiber, and at the same time, the 1.55 µm wavelength emerging from the fiber needs to be focused at a certain other position.

We have designed a mixed multilevel diffractive lens to implement the bidirectional optical fiber communication function. The simulated efficiencies for the two bandwidths are shown below. One can see that, for the 1.31 µm wavelength (a), the efficiency is as high as about 57.6%, and for the 1.55 µm wavelength (b), the efficiency is as high as about 66.5%.

* J.-R. Kropp is with the Infineon Fiber Optics GmbH.
Quite recently, it was found that [1] a simple metal wire can effectively guide terahertz (THz) waves. This unexpected finding paves the way for a wide range of new applications for THz sensing and imaging. In the initial Nature paper [1], the authors focused on the report of experimental observations, however, without a deep theoretical explanation. Here [2], we present the needed theory, explain the experimental results, and discuss some related problems.

It is well known that surface plasmons can be excited by periodic structures like metal gratings [3] and can propagate along flat metal-dielectric interfaces. Surface plasmons can also exist at cylindrical metal-dielectric interfaces. For the latter, there are one magnetic field component $H$ and two electric field components $E_r$ and $E_z$. This kind of surface plasmon can be reasonably called azimuthally polarized surface plasmon because the only magnetic field component $H$ is angular.

By use of the model of azimuthally polarized surface plasmon and the huge absolute values [4] of the relative permittivities $\varepsilon_m$ of metals in the spectral region of THz radiation, we successfully explain the experimental results [1] of low attenuation, very low dispersion, approximately radially polarization of electric field, low coupling efficiency form light source to the waveguide, high coupling efficiency between two metal wire waveguide in contact each other, and the maintained polarization state during propagation.

Generally speaking, the larger the absolute values $|\varepsilon_m|$, the better the metal wire waveguide. We suggest the use of nonmagnetic metal with very large $|\varepsilon_m|$. Copper, silver and gold are good candidates. We prefer copper because it is much cheaper than silver and gold.

![Graph showing the calculated attenuation of a copper wire waveguide with a radius of 0.45 mm, as a function of frequency. One can see that the attenuation is smaller than $2 \times 10^{-3}$ cm$^{-1}$ in the range of 0.1–1THz. This result explicitly shows the superiority of a copper wire waveguide.](image)