Investigation on metal reflection coatings of free-space optical interconnect components with integrated fan-out DOEs

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Abstract

We have designed a phase-only DOE with 1-to-9 beam fan-out functionality for optical beam distribution in an existing free-space optical interconnect (OI) component. However, due to the oblique angles of higher order diffracted beams, the condition of total internal reflection is not always met. To solve the problem, we propose to use an aluminum coating on top of the DOE and the deflecting prism sidewall. We compare experimentally a metal coated and uncoated replica of the OI component and investigate the polarization dependence of the reflectivity of the coating. We consider gold as a coating for future experiments, since the imaginary part of its complex index of refraction is smaller than aluminum's and therefore a smaller fraction of the incident light will be absorbed.

Introduction

As the processor speed and the demand for bandwidth increase rapidly, parallel optical interconnects provide a compact and potentially more efficient alternative to galvanic interconnection technology. While the number of transistors on a chip is sky-rocketing, the necessary interconnection technology is not advancing with the same pace. Optics might provide a solution for a number of problems that electrical interconnects will face in the near future. Recent advances in surface normal optoelectronic device technology (e.g. vertical-cavity surface-emitting lasers, emitting their light along the normal to the substrate) and the emergence of solder-bumping or related hybrid integration techniques to silicon circuits make optics an attractive candidate for the highly demanding interconnect task between and even within chips. However, optical interconnects should not only outperform their electronic counterparts in terms of bandwidth, power consumption and latency specifications, they should also add functionality beyond the typical point-to-point interconnects which might give micro-optics a distinct advantage over galvanic interconnect technologies. The realization of a richer set of interconnection topologies – either fixed or dynamically alterable – may be required. An interconnect in which the topological or geometrical path followed by an information stream may vary in time is called a reconfigurable interconnect. In a first step, the optical interconnection scheme could be such that the optical signal of each individual micro-laser is beam shaped by micro-optical components and fanned-out by a diffractive element to all or a limited number of detectors. This broadcasting of signals, as illustrated in Figure 1, could allow for clock distribution for example. Using resonant cavity photodetectors and/or tunable VCSELs, this scheme can be expanded to a reconfigurable interconnection pattern. Only the detector that is in resonance with the wavelength of the micro-laser will convert the photons into an electrical signal. Tuning the laser wavelength (or resonant-cavity photodetector) will thus result in addressing a different detector (or VCSEL), paving the way to dynamically reconfigurable optical interconnects.

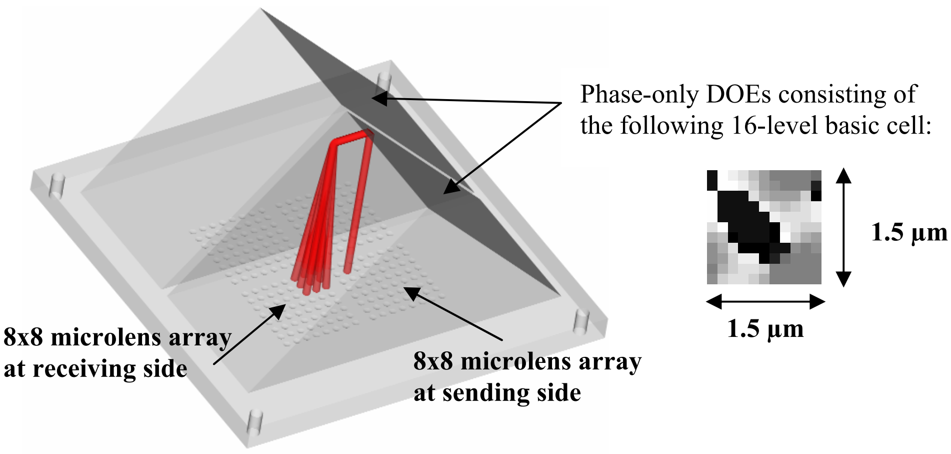

Figure 1: Micro-optical interconnection component with integrated DOEs on the prism sidewalls in order to realize optical broadcast functionality (1-to-9 beam fan-out)

Also shown in Figure 1 is the basic cell of the phase-only DOEs as it results from the design using the Iterative Fourier Transform Algorithm in VirtualLab [1]. The free-space OI component [2] is fabricated in Poly-MethylMethAcrylate (PMMA) with refractive index n_{PMMA} = 1.483 using Deep Lithography with Protons (DLP) [3].

Total Internal Reflection

The major issue that arises when incorporating a DOE with fan-out functionality in the micro-optical interconnection component is that the condition for Total Internal Reflection (TIR) is no longer always satisfied for the beam reflection on the prism sidewalls. Especially the m = +1 diffraction order beam, having an incidence angle smaller than the critical angle θ_c, will not satisfy the TIR condition, as illustrated in Figure 2. To overcome this problem, we propose to coat the prism sidewall with a metal reflection coating. In a first step we chose aluminum (Al) for this purpose. The critical angle for TIR on a PMMA-air interface is $\theta_c = 42.39°$.

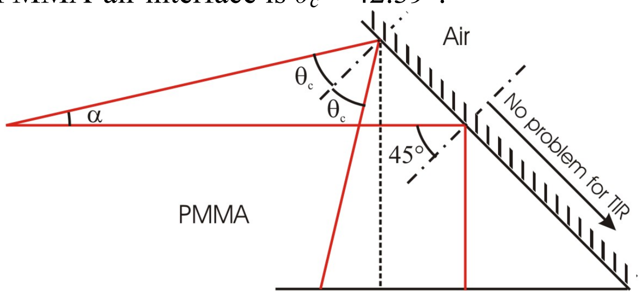

Figure 2: Problem of satisfying the TIR condition when using DOEs for beam fan-out in the OPB

Let us now analyze the reflection characteristics of an Al reflection coating applied on a PMMA (n_i = 1.483) prism. Aluminum has a complex refractive index of n_t = 1.39 + 7.65i at a wavelength of 632.8 nm [4]. From the Fresnel equations, we can calculate the amplitude reflection coefficients for an electrical field respectively perpendicular and parallel to the plane of incidence [5], if we implicitly assume that the coating is an order of magnitude thicker than the penetration depth of the metal used for the coating. To take into account that in our case the light is propagating from an optically denser medium into one which is optically less dense ($n_i > n_t$), we have to eliminate θ_t since it has a complex value when calculated using Snell's law of refraction. The equations then take the following form [5]:

$$r_\perp \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_\perp = \frac{\cos(\theta_i) - i\cdot\sqrt{\sin^2(\theta_i) - n^2}}{\cos(\theta_i) + i\cdot\sqrt{\sin^2(\theta_i) - n^2}} \tag{1}$$

$$r_{//} \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_{//} = \frac{n^2\cdot\cos(\theta_i) - i\cdot\sqrt{\sin^2(\theta_i) - n^2}}{n^2\cdot\cos(\theta_i) + i\cdot\sqrt{\sin^2(\theta_i) - n^2}} \tag{2}$$

where E_{0i} is the amplitude of the incident field, E_{0r} is the amplitude of the reflected field and $n = n_t / n_i$. The reflectance coefficients are defined as:

$$\begin{cases} R_\perp \equiv \left(\dfrac{I_r}{I_i}\right)_\perp = \left(\dfrac{E_{0r}}{E_{0i}}\right)_\perp^2 = r_\perp \cdot r_\perp^* \\ R_{//} \equiv \left(\dfrac{I_r}{I_i}\right)_{//} = \left(\dfrac{E_{0r}}{E_{0i}}\right)_{//}^2 = r_{//} \cdot r_{//}^* \end{cases} \tag{3}$$

where * denotes the complex conjugate. The reflectance coefficients as a function of the incidence angle are shown in Figure 3, as well for aluminum (Al) as for gold (Au).

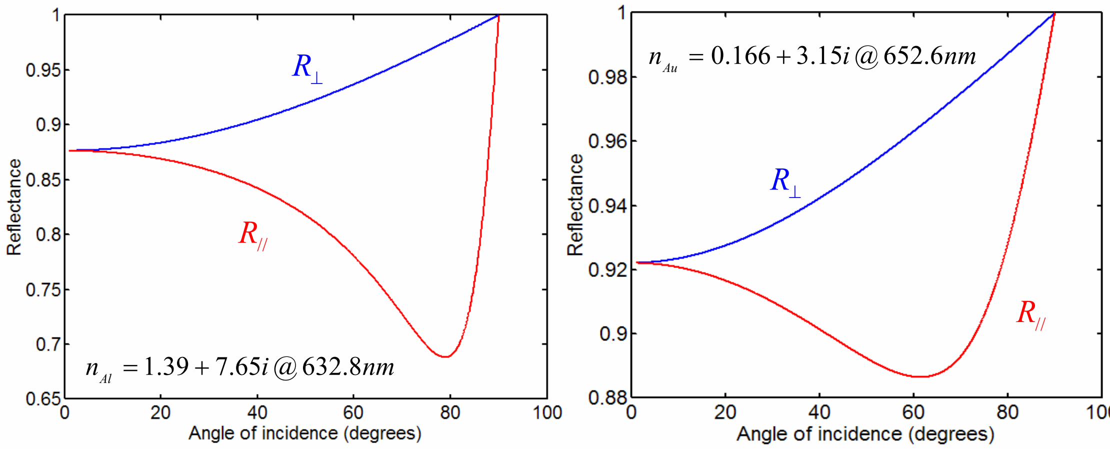

Figure 3: Reflectance as a function of angle of incidence for internal reflection on a PMMA – Al interface (left) and on a PMMA – Au interface (right)

Comparing the reflectance coefficients for Al and Au for incidence under 45° clearly shows that Au is the best choice for the coating of the free-space interconnection component: $R\perp$ (Au) = 0.95 vs. $R\perp$ (Al) = 0.91 and $R_{//}$ (Au) = 0.90 vs. $R_{//}$ (Al) = 0.83.

Comparison of a coated with an uncoated OI component

Although the problem of not satisfying the TIR condition is solved by applying a coating, the light is partially absorbed when reflecting on the coated prism sidewalls since both $R\perp$ and $R_{//}$ are smaller than 100%. Compared to an uncoated version of the OI component, in which we satisfy the TIR condition and consequently have a theoretical 100% reflection on the prism sidewalls, we thus expect a drop in transmission efficiency when applying an Al coating. This theoretically expected drop in efficiency is given by the factor p in equation (4), taking into account the polarization dependent reflection on both prism sidewalls, with $e_{0//}$ and $e_{0\perp}$ the normalized components of the electrical field.

$$p = 1 - \left(e_{0//}^2 \cdot R_{//} + e_{0\perp}^2 \cdot R_{\perp} \right)^2 \quad (4)$$

For an aluminum coating this efficiency drop lies between 17% and 31,5% (depending on the state of polarization of the incident light). The use of gold for the coating would yield a much better performance, since in that case 11,5% $< p <$ 20%.

We have experimentally verified this efficiency drop by comparing the transmission efficiency and crosstalk characteristics of an uncoated with a coated OI component. The results of those measurements are shown in Table 1. The thickness of the applied Al layer was 600 nm on average, which is about ten times the penetration depth of Al. The OI component itself was monolithically integrated in Poly-Urethane (PU) and at this point, the DOE for optical broadcast was not yet incorporated in the OI component.

	Coated OI		**Uncoated OI**	
	Min	Max	Min	Max
Transmission efficiency (%)	4,0	7,0	8,6	12,4
Crosstalk (dB)	-34,2	-20,7	-29,6	-23,8

Table 1: Results of the measurements of an OI component with and without Al coating

We observe a reduction in transmission efficiency when coating the OI component with a layer of Al. This reduction is, however, higher than the maximally expected efficiency drop. This can be explained by the fact that dust particles have been captured under the Al layer, resulting in a further decrease of the transmission efficiency. It is also possible that temperature effects are occurring when applying the coating. This should be further investigated.

Conclusion

In this paper, we have shown that the application of a metal reflection coating is necessary when incorporating a DOE for optical broadcast in our free-space OI component because the condition for total internal reflection is not always satisfied. However, incorporating a metal reflector has two main drawbacks. Due to the metal's complex index of refraction, the light is partially absorbed by the coating. Moreover the reflection on the coating is polarization dependent. We have experimentally compared the performance of our free-space OI component with and without aluminum coating. For future applications, we conclude that gold should be used instead of aluminum because of its lower efficiency drop factor.

References

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