WHITE PAPER

Nano-optics: Changing the Rules For Optical System Design

Written by Dr. Hubert Kostal
NanoOpto Corporation White Paper #001

June 2003

Nano-optics: Changing the Rules for Optical System Design

Abstract

The commercial introduction of breakthrough, wafer-based, nano-fabrication techniques allows the creation of a new class of optical components – nano-optics – with physical structures far smaller than the wavelength of light. The fine scale surface structures of nano-optics interact with light according to novel physical principles, yielding new arrangements of optical processing functions with greater density, more robust performance, and greater levels of integration when compared to many existing technologies. The revolutionarily small dimensions of nano-optics allow multi-layer integration, yielding complex optical components "on a chip" with a broad range of applications, and create fundamentally new approaches to optical system design.

1. The Next Level of Optical Component Design

Nano FAQ

Nano-optics, a new class of optical components with physical structures far smaller than the wavelength of light, allow multi-layer integration, thereby yielding complex components "on a chip" with a broad range of applications.

Integrated optical component and module design has achieved a high degree of sophistication in combining discrete optical elements. A strong understanding of the properties of optical materials and their combinations, clever optics design, and advances in alignment and assembly is applied to increase component and module density, reduce costs, and increase reliability. But there are limits. The natural optical properties of many discrete optical elements are relatively fixed, limiting the flexibility of the optical component designer and reducing transferability from design to design.

To take optical component design to the next level of density, cost, and reliability requires an enhanced set of optical element "building blocks" that can provide a broad range of tailored optical processing functionality. Discrete building blocks must have excellent optical properties while being easy to integrate with other optical materials in a broad range of configurations. In addition, these building blocks should self-integrate to allow the combination of optical functions to reduce part count and increase reliability, and to allow increased flexibility in optical component design.

A new class of optical elements – nano-optics – possessing exactly these properties is now commercially available and represents the realization of nano-technology applied to optical elements. By patterning optical materials with various nano-scale structures, a broad range of optical effects is achieved. This White Paper provides an introductory overview of the general concepts behind nano-optics and their manufacture and optical component design - and an overview of the expected results of the evolution of this technology.

2. A New Class of Optical Components – Nano-optics

The interaction of light with subwavelength grating structures – gratings with one or more dimensions one or more orders of magnitude smaller than the wavelength of the incident light – produces a broad range of controllable optical effects. In this domain, rigorous application of the boundary conditions of Maxwell's equations describes the interaction of light with the structures. Typically, the structures required to achieve these effects have some dimensions on the order of 10s to a few 100s of nanometers. At the lower end of the scale, single electron or quantum effects may also be observed.

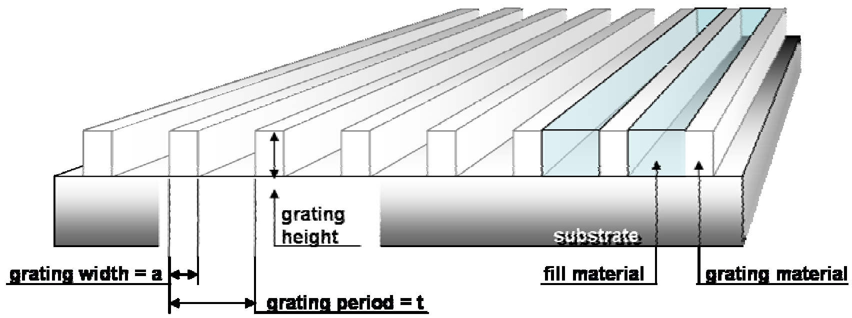

Figure 1. Adjusting the dimensions of the subwavelength diffraction grating yields a broad range of optical properties.

Nano FAQ

The optical properties of nano-optic devices can be tailored to meet application requirements by adjusting structural parameters and materials

A simple subwavelength grating structure on an optical substrate is diagramed in **Figure 1**. When light is normally incident on the nano-structure, the transmitted – that which passes through the grating structure – and reflected portions of the light are affected. The effect on the transmitted and reflected light can be varied by adjusting the size, shape, and spacing of the grating structure. In particular, for the one dimensional grating structure in Figure 1, appropriate selection of dimensions will result in behavior as a polarizer, waveplate, or polarization-dependent filter. Other effects, such as polarization independent filters, can be achieved by two dimensional gratings, such as those in **Figure 2**. The general class of these structures is referred to as nano-optics.

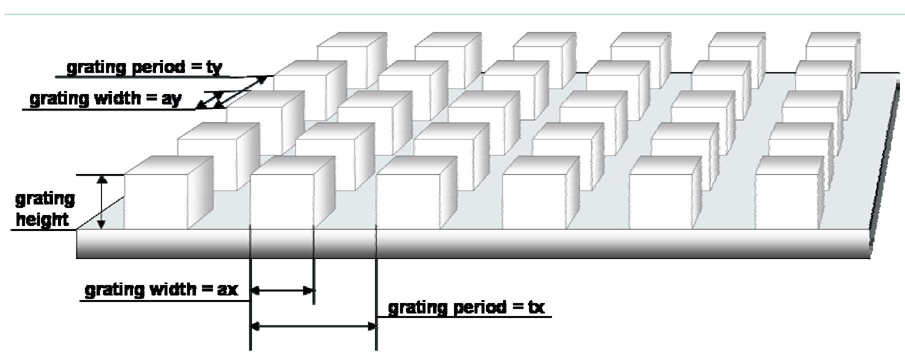

Figure 2. Multidimensional gratings allow a range of optical functions, in this case a polarization independent filter.

Because the diameter of the incident light beam is often much larger than the structures of the subwavelength grating, the effect on the transmitted light is the statistical result of numerous local interactions between the light and the grating. For example, if a light beam only 100 microns in diameter is incident on a two-dimensional grating (such as in Figure 2), and the period of the nano-structure is 200 nano-meters in both dimensions, over seven million nano-structures will be illuminated. This property can be taken advantage of by varying the grating dimensions spatially across the incident beam front, thereby allowing additional control over optical processing effects.

As manufactured, a nano-optic device is an optical chip with a subwavelength grating on one side of a substrate as shown in Figure 3. The overall thickness of the element is predominately dependent on the thickness of the substrate. The length and width of the nano-optic are selected based on application requirements. In **Figure 3**, the nano-optics are 1.4mm by 1.4mm by 0.5mm thick.

Figure 3. Nano-optics can be sized to meet optical component architectural requirements; the optical chips pictured here are 1.4 mm x 1.4 mm x 0.5 mm in size.

3. Some Basics of Nano-optic Physics

Whereas the principles of reflection, refraction, diffraction, and interference describe the behavior of traditional optical elements, when subwavelength structures interact with light, as in nano-optics, the equations describing conventional optical behavior do not fully cover the resultant phenomena because quantum mechanical effects now come into play. In many applications, subwavelength structures act as a nano-scale diffraction grating whose interaction with incident light can be modeled by rigorous application of the diffraction grating theory and the boundary conditions of Maxwell's equations.

Refraction, for example, is a key property exploited in optical components. Traditionally, different materials must be used to obtain different refractive indices. In nano-optics, however, different refractive indices can be obtained with the same material by adjusting the physical structure. As an example, nano-optic structures can be used to create an "artificial" birefringence effect. If **a** is the grating period and **t** is the grating width, then the refractive indices of the TE wave $\mathbf{n_{te}}$ (the electric vector parallel to the grating grooves) and the TM wave $\mathbf{n_{tm}}$ (the electric vector normal to the grating groove) are expressed as:

Nano FAQ

Nano-pattern transfer provides a consistent process for creating a broad range of nano-structure patterns.

TE wave, $$\mathbf{n_{te}^2 = R\, n_1^2 + (1 - R)\, n_2^2}$$

TM wave, $$\mathbf{n_{tm}^2 = n_1^2\, n_2^2 / (R\, n_2^2 + (1 - R)\, n_1^2)}$$

where $\mathbf{n_1}$ is the dielectric constant of the grating material, $\mathbf{n_2}$ is the dielectric constant of the fill material, and **R** is the ratio of the grating width to the grating period **r = t/a** (see Figure 1). By choosing the nano-optic material and adjusting the ratio **R**, a birefringence effect can be achieved that is much larger than that achieved with standard optical materials.

Many nano-optics have periodic patterns, and therefore may be viewed as optical gratings. When incident light is perpendicular to a grating surface, the conventional grating equation can be expressed as

$$\mathbf{a \sin \theta_m = m\lambda}$$

where **a** is the grating period, **m** is the diffraction order, $\theta_\mathbf{m}$ is the diffraction angle, and λ is the wavelength of the diffracted light. When the grating period is less than the wavelength, as in nano-optics, the incident light is still subject to grating diffraction. However, no higher order diffraction occurs - all the diffracted optical energy of the incident light will be of zero order. This results in nano-optics that have relatively uniform performance across a broad range of wavelengths and wide acceptance angles.

4. The Manufacture of Nano-optics: Nano-pattern Transfer

Nano FAQ

Nano-pattern transfer overcomes previous manufacturability and nano-structure pattern consistency limits

With this sort of flexibility, why are nano-optics just now becoming available for optical system applications? The primary reason has been manufacturability. While the optical effects that result when light passes through nano-scale structures have been studied for at least 20 years, cost-effective manufacturing of these optical elements has not been available. Building subwavelength grating structures in a research environment has generally required high energy techniques, such as electron beam lithography, or extremely precise process controls to grow nano-structures, such as via molecular self alignment. A second reason has been the lack of a consistent process for creating a broad range of nano-structure patterns. Many techniques for creating nano-structure patterns are limited in the range of patterns that are possible.

Nano-pattern transfer is a manufacturing method that overcomes these limits. The process involves several key steps: constructing a mold inscribed with the complement of the desired nano-pattern, transferring the pattern to a resist layer on a prepared substrate, and selectively removing the resist with reactive ion etching to transfer the nano-pattern to the target material layer on the substrate (see **Figure 4**).

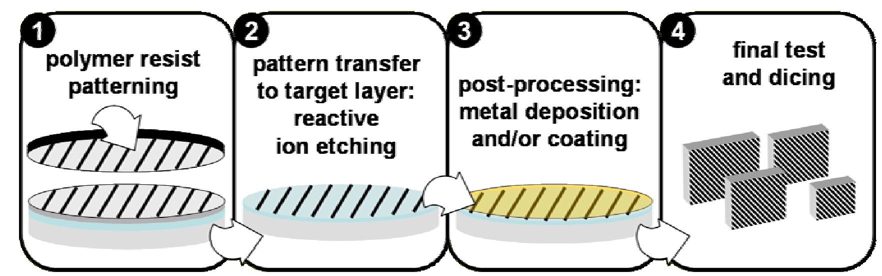

Figure 4. Nano-pattern transfer is a highly scalable and flexible technology for fabricating nano-optics.

After this, additional processing steps may be used to add other materials to modify or enhance optical performance. Also, coatings may be added to mitigate reflection and for protection to allow ease of handling in a standard manufacturing environment. Testing and dicing follow, yielding the end result of optical chips such as those shown in Figure 3. Because nano-pattern transfer forms the nano-structures of nano-optics by a direct, physical process rather than by beams of energy, the effects of wave diffraction, scattering, and interference in the resist do not limit fabrication resolution.

Silicon dioxide or silicon is commonly used to make a mold patterned with the desired nano-structures. Various techniques, including electron beam lithography, can be used to create the desired negative image of a nano-structure. Because the mold can be replicated and re-used, complex multi-step and multi-process methods can be used to create the desired nano-structure. Since these initial tooling steps do not need to be repeated for each production wafer, they are amortized over the full production run of a particular nano-optic. Using different molds with different nano-structure patterns allows the same manufacturing process to create the full range of nano-optics.

5. The Use of Nano-Optics in Optical Component Design and Manufacture

The practical consequences of using nano-optics can be explored by looking at a specific realization – a nano-optic polarization beam splitter / combiner (PBS/C). By appropriate selection of the dimensions of a one dimensional subwavelength grating structure, one polarization will be transmitted while the orthogonal polarization will be reflected as illustrated in **Figure 5**. At this scale, the subwavelength diffraction grating exhibits only zero order diffraction, resulting in a number of useful element characteristics. These include consistent performance across a broad range of wavelengths. A nano-optic PBS/C grating designed for telecom applications, for instance, has uniform performance for wavelengths ranging from 980nm to 1800nm. Additionally, wide variations in the angle of incidence of the light beam – up to 20° of deviation from normal – result in no appreciable change in performance. Typical performance parameters for a nano-optic PBS designed for telecom applications have an insertion loss of less than 0.13dB on both the reflected and the transmitted beams. Extinction ratios are greater than 40dB and 20dB for the transmitted and reflected beams, respectively. The flexibility of nano-optic designs allows various application-specific performance tradeoffs to be made around these parameters.

Nano FAQ

The benefits of a PBS/C nano-optic are realized in their optical component size and in the assembly process, which reduces manufacturing time and cost.

The benefits of a PBS/C nano-optic are realized in two areas. First, there are architectural benefits in optical component design. Because of their small form factor, they allow more compact component designs. This results in both smaller footprint and reduced packaging costs. Because nano-optic can be abutted to other elements with minimum free space separation, reduced insertion losses are also realized. Because of differences in the way that the elements handle light - for instance, the polarization beam splitter is a reflective device with 180° of effective separation obtained in less than a micron – the beam path can be laid out to simplify device design and potentially eliminate other optical elements. Additionally, the reflective nature of the nano-optic PBS allows it to support high energy applications associated with laser transmitters and fiber amplifiers.

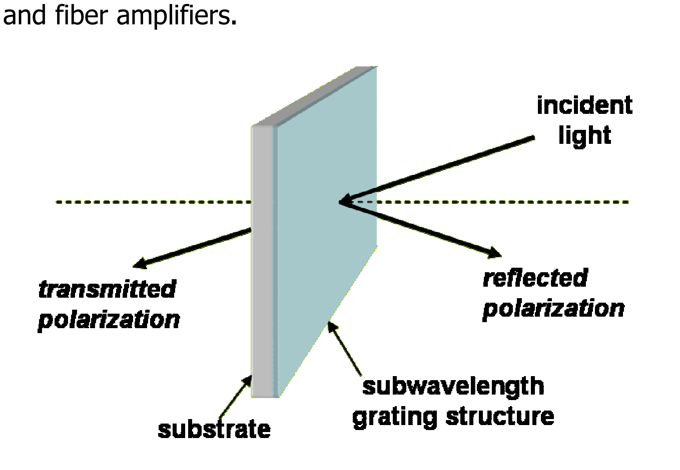

Figure 5. A subwavelength grating based polarization beam splitter achieves 180° of effective separation in a nano-optic layer less than 1 micron thick.

Second, there are advantages in assembly. The wide acceptance angle simplifies the alignment process, reducing manufacturing time and cost. It is also possible to readily use automated "pick and place" manufacturing technologies. The robustness of the nano-optics – with proper selection of materials they can be subjected to temperature ranges of -200°C to 400°C – allows them to be used without compromise in a broad range of manufacturing processes. Finally, the small size can both simplify packaging and reduce packaging costs.

The nano-optic PBS/C has application in fiber amplifiers, circulators and isolators, interleavers, optical switches, and variable optical attenuators. In these applications, when compared to existing technologies, nano-optics are very efficient. This is because traditional optical materials require a significantly larger size to create the same optical effect. In addition, materials that use non-diffractive optical effects, such as absorptive resonance, may have power handling limitations.

6. The Future of Nano-optics

Current devices represent the initial applications of nano-optics. As applications are extended, the possibilities expand in several dimensions. First, additional nano-optic based building block functionality will be introduced both as chips and as packaged devices. Demonstrated nano-optic functionality spans polarizers, polarization beam splitters/combiners, filters, photodetectors, and photonic band gap devices. Dynamic control for switching, attenuation, and tuning are also demonstrated capabilities.

Nano FAQ

Nano-optics allow multi-layer integration, yielding complex optical components "on a chip" with broad application to optical networking and with the potential for fundamentally new approaches to optical systems design.

Monolithic integration of nano-optics can be achieved by stacking nano-optic layers to create aggregated optical effects. Nano-pattern transfer permits direct layering on nano-optics without resorting to lamination techniques. Combining nano-optics with optically active layers allows optical control circuits to be built, resulting in complex optical components "on a chip". Multi-layer nano-optic integration has already been demonstrated by combining filters with photo detector arrays to create dynamic optical feedback loops.

Nano-optics offer a new design vocabulary for the integration of optical functions. By providing a broad range of fundamental building blocks for optical component and module design, new functions and combinations of functions are now possible. In addition, because nano-optics are fabricated via wafer-scale manufacturing processes with relatively minor differences from device to device and are self compatible, the means exist to implement this design vocabulary. By utilizing the nano-optic design vernacular, the real possibility exists that optical system design can be systematized, resulting in uniform functionality. In addition, the building blocks can be combined to generate a much more direct approach to integration (indeed integration that is "programmable"). The foundations for these advances are being built today. A steady flow of advances can be expected over the next few years, along with a proliferation of custom nano-optic designs for heterogeneous integration and arrays.

The Company

NanoOpto Corporation applies proprietary nano-optical and nano-manufacturing technologies to design and fabricate novel components for optical systems and networks. The company's core capabilities enable it to deliver orders-of-magnitude advances in prototyping speed, component performance, and reduced system cost.

Backed by leading venture capitalists, the company has established headquarters and a high volume nano-pattern transfer manufacturing facility in Somerset, NJ. Here, working both independently and with corporate partners, NanoOpto is creating new classes of densely integrated, modular nano-optic components.

Compared to the conventional, bulk optical components, NanoOpto's optical components offer such superior cost/performance that they expand the range of commercially practical applications for optics across multiple industries.

Our Products

NanoOpto offers a growing, coherent family of optical systems building blocks – modular nano-optics. These consist of optical nano-patterns fabricated on optical wafer substrates and then diced to create compact, high-performance optical chips.

Contact Information

For more information, contact sales@NanoOpto.com or visit www.NanoOpto.com.