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Binary Optics: Trends and Limitations

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1. ABSTRACT

We describe the current state of binary optics, addressing both the technology and the industry (i.e., marketplace). With respect to the technology, the two dominant aspects are optical design methods and fabrication capabilities, with the optical design problem being limited by human innovation in the search for new applications and the fabrication issue being limited by the availability of resources required to improve fabrication capabilities. With respect to the industry, the current marketplace does not favor binary optics as a separate product line and so we expect that companies whose primary purpose is the production of binary optics will not represent the bulk of binary optics production. Rather, binary optics' more natural role is as an enabling technology - a technology which will directly result in a competitive advantage in a company's other business areas - and so we expect that the majority of binary optics will be produced for internal use.

2. INTRODUCTION

The goal of this paper is not technical. We assume the reader is familiar with the technology of binary optics (see the other papers in this proceedings) and our goal is to describe the current state of the binary optics field. More specifically, we intend to answer the following three questions:

- What is binary optics?
- What is the future potential of the technology?
- What are the factors limiting growth?

We will answer these questions both from a technical standpoint and also from an industry (i.e., marketplace) standpoint. Naturally, the answer to such questions must be somewhat subjective and the reader should recognize that our viewpoint is from a national laboratory whose goal is to cooperate with industry and government to develop this technology.

In answering these questions, we will use the following approach. In the remainder of this section, we will first develop a working definition for "binary optics" and then introduce some classification schemes for binary optics, in order to gain some insight into the field. In section 3, we will examine the current state of the binary optics technology, using one of the previously introduced classification schemes and in section 4, we will repeat this process for the industry as a whole. Finally, the last section will summarize the major points of this paper.

Table 1: Fields Related to Binary Optics.

Related Field	Why Is It Not Binary Optics?
Conventional Lenses	Conventional Fabrication
Holographic Optical Elements	Optical Fabrication, Volume Effect
Gradient Index Optics	Volume Effect
Optical Coatings	No Surface Relief
Non-linear Optics	Volume Effect, Active
Photorefractives	Volume Effect, Active
Liquid Crystal Displays	Active, Not Purely Surface Relief
Integrated Optics	Guided Wave Optics
Microelectronics	Not Optical, Active
Micromechanics	Not Optical, Active

2.1. Definition

What is binary optics? This basic question is not easily answered because there is no strict definition. Binary optics is a somewhat general term, invoking radically different images to different people. For example, to an optical designer, the meaning of binary optics is coupled to the application but that application may be any of the following: diffractive lenses for use in laser systems, aberration correction of wideband systems, null testing of aspheric elements, intraocular lenses, stereo vision systems, laser scanners, grating beamsplitters, read/write heads for optical data storage, custom diffusers, optical interconnects, laser cavity optics, beam shaping of lasers, laser diode collimation, fiber couplers, microlenses, anti-reflection surfaces, artificial index materials, artificial birefringent materials, etc. On the other hand, to a person involved with the fabrication aspect, binary optics may suggest the following activities: mask writing, photoresist exposure and development, analog exposure of resists, planarization of topology and tri-layer resists, mask alignment, dual-sided alignment, reactive ion etching, ion milling, wet chemical etching, laser chemical etching, laser ablation, laser writers, direct e-beam writers, chemical vapor deposition, liftoff deposition, metallization, sputtering, etc. These areas are all part of binary optics, yet they are so diverse that it is difficult to come up with an explicit definition which will fit them all. Therefore, we will not attempt this. Instead, we will define the field through descriptions and examples, an implicit definition of sorts.

As a first example, we consider closely related fields and ask why these fields are not considered part of binary optics. Table 1 lists a number of these fields and the differences between them and binary optics. Analyzing this list then yields the following distinguishing features:

- Surface Relief - The optical properties of binary optics are solely the result of the surface profile of the element. Volume effects are not significant, as with thick holograms, graded index optics or photorefractives. As a corollary, this property allows the possibility of inexpensive replication methods, such as embossing.

- VLSI-based Fabrication - Binary optics are manufactured using semiconductor fabrication technology. This allows the fabrication of elements with sub-wavelength precision and also the potentially simpler integration of optics and electronics.
- Free-space, Passive Optics - Binary optics are passive optical elements to be used in free-space applications. By free-space, we mean systems where a large number of modes are propagating (i.e., everything except guided wave systems).

Taken together, these characteristics provide a loose current definition of binary optics. As the field evolves, however, this definition will also change accordingly.

2.2. Classification Schemes

In order to further describe the field, this section considers different methods of classifying binary optics. In other words, we ask how can binary optics be subdivided.

One method of classification is by historical development. The evolution of binary optics over the past decade can be divided into three generations. The first generation focussed on elements with large features. Accordingly, the majority of applications were large individual elements (macro-optics) used for the residual aberration correction of conventional systems. This generation is now relatively mature and has been largely transferred to industry. Advancing fabrication techniques resulted in smaller feature sizes, thus spawning the second generation: microoptics and arrays of microoptics (especially microlenses). At present, this generation has progressed to the point of attracting much industry interest and activity but it is still far from mature. Further advances in fabrication and packaging are leading to the third generation, which will see the integration of optics and electronics/electro-optics. This generation is largely still in the laboratory - and only a few laboratories at that. However, this technology has a large commercial potential and as soon as it is clear how this potential may be realized, interest in this area will increase exponentially. Reviewing the history of binary optics shows that it is based on the evolution of fabrication capabilities. As fabrication capabilities increase, the technology progresses from generation to generation. The evolution of the fabrication technology is a natural one, but the resulting applications are not necessarily related. For example, compare the design of a FLIR telescope (first generation) with the design of integrated components for optical data storage systems (second or third generation). This is one reason why a definition of binary optics is so difficult.

Another way to classify binary optics is by application domain. Just running through the previously mentioned applications shows that binary optics can play a role in the areas of medicine, optical communications, data storage, entertainment, displays, electronic imaging, electro-optic warfare, photolithography equipment, surveillance and optical testing, to name a few. The good news is that binary optics can be used in many different domains. The bad news is that in each of these domains, binary optics is an enabling technology rather than the focus of an industry. For example, those working in electronic imaging might use binary optics to improve the performance of their systems, but they would not say that their field is binary optics. In short, there is not a separate application domain called binary optics.

Another method to classify binary optics is by the tasks required in the design and fabrication of binary optics. There are basically four tasks required. The first is the optical design of the element. The second is the translation of this optical design into a fabrication prescription (e.g., a set of masks or the commands to run a laserwriter). The third task is the actual fabrication of the element and the final task is the testing of the completed element. Of these tasks, optical design and fabrication are the dominant tasks. This approach is especially useful when discussing the technology of binary optics and we will follow it in section 3.

Analogously, we can use a similar method to discuss the current state of the industry. Specifically, we can classify organizations involved in binary optics according to their organizational goals, of which we have identified three possibilities. First, the organization could view binary optics as their major product line, with the goal being to profit from selling binary optics. Second, the organization's major business might not be binary optics, but the organization could use binary optics as an enabling technology to support their major product line. Third, and this is pertinent primarily for new technologies such as binary optics, the organization's goal could be research in binary optics. We will follow this classification scheme in section 4.

3. THE STATE OF THE TECHNOLOGY

In discussing the technology, it is useful to consider the classification of binary optics by task, with the emphasis on optical design and fabrication since these are the dominant technological areas:

- Optical Design - There is not one set of characteristics (other than omniscient) that would describe the ideal binary optics designer. This is because the application areas are extremely diverse and because the methods used to design the elements are also widely varying. In addition to designing elements, the designer is also often tasked with the more difficult problem of thinking up new applications.
- Translation - The translation of an optical design into a fabrication prescription is primarily a problem of software availability, optimized computer programming and efficient data management.
- Fabrication - On paper, fabrication appears straightforward. In reality, fabrication is very involved and there is a substantial learning curve, typically taking years to bring up a fabrication line from scratch. It is not uncommon for experts in microfabrication technology to have accumulated several decade's worth of knowledge and experience. In addition, fabrication requires capital and progress in fabrication is usually limited by the availability of resources - both financial and personnel.
- Testing - This is the tail end of optical design and therefore faces the same problems: diverse application areas and varying testing methods.

3.1. Optical Design

The task of optical design can be further subdivided according to which theory is used to model the binary optics element:

- Geometrical optics
- Scalar diffraction theory
- Vector diffraction theory for periodic structures
- General solution of Maxwell's equations

Of these areas, designs which require only geometrical optics are the most mature and this is the only area where commercial ray trace codes are commonly used. The most common example of this design type is the use of binary optics to correct the aberrations of conventional wideband imaging systems (e.g., a telescope). In this instance, a commercial ray trace code is used to design the system and the binary optics element is modelled using either the Sweatt model or the holographic optical element option in the ray trace code. The use of binary optics allows additional degrees of freedom in the design and a designer schooled in "classical" lens design principles would be the most adept at taking advantage of this. The resulting binary optics piece is typically a single element with large features. Since this type of application was among the earliest, it is also among the most mature, with some designs currently in production phases. The intraocular lens, a human lens replacement, is another design based on geometrical optics, except with the twist that the diffractive lens portion uses two foci (a phenomenon predicted by scalar theory). Another type of geometrical problem is the design of optics to incoherently couple as much energy as possible from a source (typically an array of LED's or lasers) to a sink (typically a fiber or detector). The design is based on tracing rays, but since the application is photon collection and not imaging, the usual ray trace codes are typically not used and the resulting design is often an array of microoptics, a far cry from an imaging system.

In the realm of scalar designs, the binary optics element is modelled using one of the scalar diffraction theories. The commercial ray trace codes are not applicable and the models are typically built on either matrix manipulation packages (e.g., IDL, MATLAB, etc.) or programming languages (e.g., C, Fortran, etc.), with the builder of these models having a background in Fourier optics and numerical methods (signal processing would not hurt either). A popular application is the design of grating beamsplitters (e.g., a grating which produces N uniform diffraction orders). There are several ways to solve this problem: the solution of non-linear equations (Dammann gratings), the use of an iterative phase retrieval method (e.g., Gerchberg-Saxton) or some form of search and/or optimization (e.g., Nelder-Mead or exhaustive search). The reader will note that these problems are substantially different from the geometrical design problems and so too is the background required to design this type of element. A second application example is the design of laser cavity optics, for example, to coherently couple lasers. Again, this design is based on Fourier optics and requires the knowledge of a physicist or Fourier optics.

In the realm of vector designs, the solution of Maxwell's equations for an arbitrary element is still too numerically expensive to solve for almost all cases of interest. Instead, we currently are limited to solving Maxwell's equations for periodic structures. The diffraction from gratings can be solved via a decomposition into space harmonics or a decomposition into the eigenmodes of the grating. In either case, the ideal person to analyze and design these elements would be a mathematician with

Table 2: Current State of Optical Design.

Design Domain	Maturity of Design Concepts
Geometrical Optics	Design concepts understood by industry.
Scalar Diffraction Theory	Design concepts understood by researchers.
Maxwell's Equations for Periodic Structures	Early design concepts being formulated.
General Maxwell's Equations	Analysis possible only for simple cases.

numerical methods background. Examples of applications in this regime would be anti-reflection coatings (artificial index materials) and artificially birefringent materials.

Table 2 summarizes the current status of optical design technology, with the left hand column listing the different design domains and the right hand column describing the maturity of each domain. As for future areas of interest, there are several. One obvious area is continued work in each of the areas in table 2. This will require the further development of theories (e.g., to build intuition) and the improvement of numerical methods (e.g., to efficiently solve Maxwell's equations for the general case). As the technology matures and moves onto the factory floor, another challenging area will be the solution of practical problems: manufacturing tolerances, handling procedures, quality control, etc. Yet a third domain of interest is the integration of binary optics with other technologies. For example, a monolithic compact disk head would require the common packaging of optics, sources and detectors. Finally, the biggest challenge facing the optical designer is the discovery of new applications. However, this is somewhat of a catch-22. You can't think of any new applications if you don't know what the capabilities of binary optics are, but you can't spend the time to learn about binary optics if you don't have a potential application.

3.2. Translation

After the optical design process is completed, the optical design must be translated to a fabrication prescription. For example, the mathematical description of an aberration corrector may be translated into a set of masks. There are a number of well-known ways to do this: following contours, bitmapping, sampling and interpolating, analytical solution, etc. However, there is not a single method which is appropriate for all cases and there is no commercially available software to accomplish these tasks. Therefore, everyone must learn and implement these translation algorithms themselves. The software that is available for VLSI layout is useful but it is designed for circuit layout and so is not exactly matched to the needs of binary optics. Specifically, the software does not implement any of the common translation algorithms, although it does allow the previewing of masks and can convert graphical layouts to common mask formats (e.g., MEBES, GDSII, etc.), and the software is expensive and includes unnecessary features (e.g., IC design rule checking). The translation task is primarily a computer task and is limited by computer performance, both in terms of speed and data volume. As computers become faster and can handle more data, the translation task will also become easier.

3.3. Fabrication

Fabrication is an extremely involved topic. A discussion of the different fabrication methods and their potential advantages and disadvantages is far beyond the scope of this paper (see Stern, "Fabrication of Binary Optics," elsewhere in this proceedings). Instead, we will examine the fabrication task by considering the characteristics of an ideal fabrication process:

- Accuracy - Fabricated elements should match their fabrication prescriptions. For optical components, the process must have sub-wavelength resolution in all three dimensions.
- Flexibility - The ideal fabrication system should be able to handle many types and size of substrates. It should also be able to handle shallow and deep features, regardless of aspect ratio.
- Reliability - The process should be both reliable (minimum downtime) and reproducible (infrequent calibration).
- Low cost - Of course, less cost is better.
- Speed - Naturally, fast turnaround is also desirable.

How does the current state of fabrication measure up to these ideal standards? Table 3 shows some "typical" numbers for three types of binary optics, with the accuracy and flexibility goals each subdivided into three criteria. The task considered is that of producing the very first element of a custom design (i.e., an initial master) and the figures are for fabrication processes requiring multiple masks, although we expect that comparable tasks using other fabrication processes will post comparable numbers. This type of task is the most expensive and time-consuming since we are at the most unfavorable point of the learning curve and do not consider the advantage of mass production techniques. Naturally, any following elements will be less problematic.

Simple elements are typically made by taking advantage of printing service bureaus, buying low-resolution photomasks, photoreducing plots made on large plotters or using some sort of laserwriter (e.g., a converted drum scanner). They are usually limited to binary elements, either amplitude or phase, since the writing of alignment marks requires higher resolution than is available and the repeated align and etch processes drive up the cost. A possible exception would be fabrication methods which rely on analog exposure of photopolymers. These methods may be able to produce low resolution multi-level elements while remaining in the simple category. The standard element represents what is normally seen on viewgraphs - a multilevel diffractive device utilizing an existing process. It is assumed that minimal process development is required although, at the minimum, new masks will be required. Finally, the exotic element has some aspect which requires considerable process development. This aspect could be unusually small feature sizes, new materials systems, large exposure areas or deep features.

Regarding future areas of interest, each of the desired characteristics (accuracy, flexibility, etc.) coupled with a specific fabrication method will result in a set of fabrication demands. For example,

Table 3: Current State of Fabrication.

	Simple Element	Standard Element	Exotic Element
Minimum Feature Size	10 μm	1 μm	0.3 μm
Feature Placement Accuracy	1 μm	0.2 μm	$< 0.1 \mu m$
Levels (Vertical Resolution)	Binary	Typ. 8 or 16	Typ. to 64
Substrate Materials	Quartz	Quartz, Silicon	Many
Substrate Diameter	3 inch	4 inch	8 inch
Maximum Surface Relief	2 μm	2 μm	10 μm
Process Reliability	Guaranteed	Processes understood	New processes
Cost	$100's to $1000's	$1000's to $10,000's	$10,000's to unlimited
Speed	Days to Weeks	Weeks to Months	Many Months

for systems based on multiple masks, the accuracy goal will require good mask-to-mask alignment and etch depth control; while for systems which rely on analog exposure of resists, accuracy will require good characterization and control of the resist exposure and development. The future task, then, is to improve the fabrication processes in order to meet these demands. Unfortunately, the nature of process development is usually arduous, unglamorous, time-consuming and money-intensive.

3.4. Testing

As a result of the various number of applications of binary optics, the testing of binary optics is also varied. In some cases, well-known test procedures can be directly applied to systems with binary optics components (e.g., the MTF testing of a telescope system with binary optics correctors). However, in many cases, new tests or variations of standard tests must be developed. For example, in the case of testing diffractive microlens arrays, one would want to measure the wavefront quality of individual microlenses, the diffraction efficiency of individual lenses and the uniformity of the entire array. These tests are commonly required but are not standard optical tests. As the technology progresses, we expect that tests of this sort will be identified, developed and then standardized.

4. THE STATE OF THE INDUSTRY

We now shift gears and consider the current state of the binary optics industry, focussing on marketplace issues rather than technical ones. In this discussion, we will use the classification of binary optics by organizational objective:

- Major Product - Some organizations view binary optics components as a major product line with the intent to profit from selling binary optics components. The current industry structure does not favor this approach and so we do not expect the bulk of the market to fall in this category.
- Enabling Technology - Some organizations use binary optics elements internally to improve

sensitivity of his products, the FLIR producer who uses binary optics to correct the aberrations of a telescope, the supplier of laser welding equipment who uses binary optics to shape the laser beam, etc.

However, the fact that binary optics is an enabling technology and not an organization's major product line has its own implications. First, the technology will not progress as quickly since it is not the focus of the company. The risk is that the company may later find itself at a competitive disadvantage because it lacks crucial binary optics technology. Small companies are especially vulnerable since their resources are more limited and they cannot spread the cost of technology development over several product lines or larger product volumes. One way to avoid this possibility without paying the full price for internal development is the cooperative establishment of consortia focussed on binary optics. Second, the fortunes of those working on binary optics technology will be determined by the fate of the major product line. The best binary optics person working in support of an ill-fated product will be ill-fated and his contributions may also be unappreciated. Third, much of the technology development will be proprietary, resulting in much reinventing the wheel (and the corresponding duplication of costs).

4.3. Research in Binary Optics

For organizations whose primary mission is research in binary optics, the current areas of interest are summarized in the technology section of this paper. Here, we point out some characteristics of the industry which affect the nature of research and research funding. First, in the current economic climate, research will be pulled by applications. It is difficult to secure research funding for the sake of technology development alone. Any research must have the promise of solving some problem. It is primarily the optical designer's or manager's task to make the match between binary optics and potential applications. However, although research is pulled by applications, it is the fabrication which makes the difference between paper research and real progress. After all, diffractive optics ideas have been around for a long time. It is the recent advances in fabrication which have spawned the binary optics industry. Therefore, we feel that most significant research must include fabrication. Having made this point, it should be noted that fabrication in a research environment cannot be expected to pay for itself. Previously, we argued that companies whose primary purpose is to turn a profit face significant market obstacles. It is unreasonable to expect research units, which are also constrained to always developing new ideas and prohibited from doing volume production, to do the same. Therefore, it should be expected that fabrication research in binary optics will have to be supported by grant money, usually from the government or from company internal funds.

5. SUMMARY

Table 4 summarizes the current state of the technology, with the two most important tasks being optical design and fabrication. In the area of optical design, we expect continued development of theories and numerical methods for designing elements in the scalar and vector diffraction regimes (modern optics designs). As binary optics moves into production, we also expect more emphasis on real world issues: manufacturing tolerances, packaging considerations, integration with electro-optics, etc. The primary limitation facing the optical designer is his creativity in thinking of new applications. In the area of fabrication, the trends follow the same lines as in the semiconductor

Table 4: Technology Trends and Limitations.

	Trends	Limitations
Optical Design	Modern Optics Designs, Manufacturing Issues	Human Innovation
Translation	Computers	Software Availability
Fabrication	Cheaper, Larger, Finer, Faster	Time and Money
Testing	Standardization	Cooperation

Table 5: Industry Trends and Limitations.

	Trends	Limitations
Major Product Line	Niche Markets, Consultants	Unfavorable Industry Structure
Enabling Technology	Bulk of the Market, Good Growth	Low Priority, Proprietary Efforts
Research	More Applications	Ideas and Funding

industry, pushing for ever smaller features, larger wafers, etc. As with the semiconductor industry, the major limitation to progress in fabrication is the time and money required to develop the technology.

Table 5 summarizes the current state of the industry. There are two major points. First, we believe that the structure of the industry does not favor organizations which view binary optics as their major product line. These organizations will be prevented from growing into large companies, although they could be quite successful in niche areas. Second, we believe the bulk of the market will be with organizations which view binary optics as an enabling technology and take advantage of binary optics to build a competitive edge in their other product lines.

Finally, we make the following two concluding remarks. First, we expect that binary optics has excellent future growth potential. It is a technology which has already been transferred to the manufacturing floor in some applications and we expect that it will become a significant component in many more applications in the future. However, the success of binary optics will be somewhat hidden since binary optics is undeniably an enabling technology. There will not be an array of successful binary optics products. Rather, there will be an array of products from diverse areas which will have used binary optics to improve their performance, reduce their weight, increase their reliability, etc. Second, the key to binary optics is the synergy between optical design and fabrication. Without fabrication, binary optics is no more than a collection of paper concepts missing the final link to reality. Without optical designs, binary optics is no more than a collection of geometrical patterns etched into a surface. In other words, the sale is made based on the merits of an optical design, but the payment is collected based on the fabrication of an element.

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