Methodology to simulate parasitic reflection and birefringence in optical pickup units and sensors

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ABSTRACT

A novel technique is presented for the computation of the polarization transfer function of optical assemblies with finite reflection coefficients, birefringence, and other parasitic imperfections. The methodology is directly applicable to optical data storage modeling, such as CD/DVD recording optics and the physical recording process.

Keywords: Optical data storage, optical system design

1. Introduction

Jones calculus [1] is a powerful tool for the modeling of optical assemblies of all types and has been particularly useful for the modeling of the optical pickup unit (OPU) in optical data storage drives [2] and optical sensors [3]. For this type of calculation, Jones matrices, which represent the optical elements, are matrix-multiplied to represent the overall optical train in a unidirectional manner. Bidirectional propagation is often handled by "unfolding" the optical train, i.e. topologically mapping a bidirectional problem into a unidirectional, albeit less compact problem.

However, the transfer-matrix approach has limitations when solving for optical systems that have re-entrant (loop) topologies. This would include optical systems with closely packed optical elements having less than perfect antireflection coatings such as an OPU. In the case of interferometers, and optical systems with partially coherent light in general, finite reflections along with the forward and backwards propagation make all but the simplest systems challenging to reduce to tractable equations.

In this paper, a methodology is introduced which is a powerful technique that permits the straightforward calculation of the polarization transfer function including the recursive mathematics that arise from the physics of multiple reflections. Although this is a generally applicable tool, is most valuable to provide a means to do tradeoff analyses for realistic components. For cost reduction, molded-optics without AR coatings may be employed in low cost OPUs, which increases the need to understand how parasitic effects will manifest themselves. Evaluation of system sensitivity to thickness, reflectivity, and birefringence variations in the media, as a function of OPU component and assembly tolerances may also be performed in a straightforward manner.

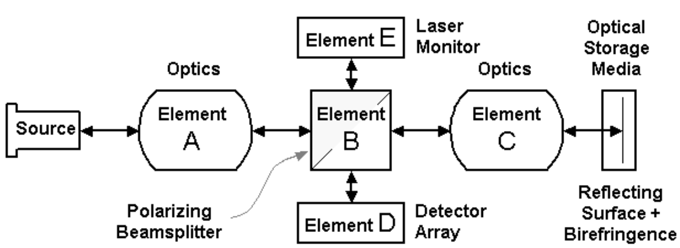

Fig. 1. OPU Elements, which in this model are representing (A) Isolator, (B) Polarization Beamsplitter, (C) Retarder, (D) Propagation to a detector, and (E) Attenuator or "dead end".

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Figure 1 shows a very simple block diagram of an OPU system, which consists of two-surface elements such as polarizers, isolators, and retarders, and a four-surface element typified by a beamsplitter.

2. Assumptions and methodology

The light that travels between the elements may be decomposed into orthogonal polarizations with respect to a common frame of reference. The approach does not operate on k-vectors like a ray-tracing program, and thus the technique does not account for the spatial nature, focusing, fringe pattern, or diffraction effects of the system. It implicitly assumes a uniform phase and state of polarization (SOP) across the optical beams, which is valid for collimated light, weakly guided, and mildly diverging light. However, this assumption is valid only to first-order for light in a high Δn waveguide or the beam waist of a high-NA objective lens [4]. Referring to Figure 2, the formalism is carried out in the following steps:

- Each surface of every optical element or sub-element is given a unique identifying number, for the x- and y-polarization states, using a careful and consistent naming convention for surfaces and ports.
- The various Jones matrices that represent the various optical elements in the system are collected.
- The Jones matrices are converted to scattering matrices, which support bidirectional propagation. Figure 2(ii) illustrates this step, for the case of a reciprocal element with no backscattering.
- The 4×4 and 8×8 scattering matrices are concatenated along the diagonal of an $n\times n$ scattering matrix S.
- A $1\times n$ column vector E_{out} represents the fields exiting every port at a given point in time.
- Another $1\times n$ column vector E_{in} represents the fields entering every port at a given point in time.
- An $n\times n$ connectivity matrix G is written by inspection having terms equal to 1 or 0 to account for geometry. This will be a symmetrical matrix, and can represent an arbitrarily complex assembly of elements. Figure 3 illustrates the connectivity between ports $3\to5$, $4\to6$, $5\to3$, and $6\to4$.
- Software such as Mathematica™ or MatLab™ is used to evaluate and apply the transfer function H.

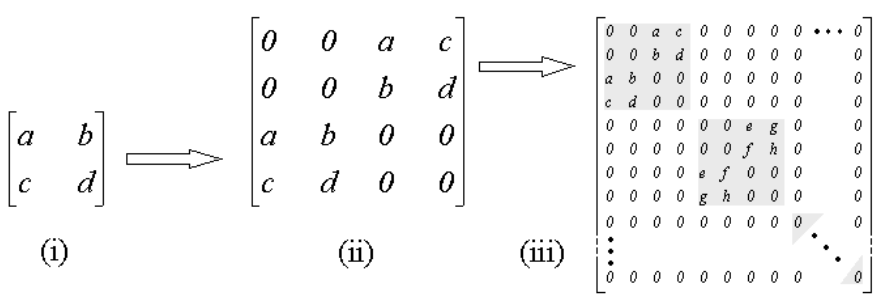

Fig. 2. S-matrix Development: (i) Jones matrix describing individual element A, (ii) bidirectional scattering matrix of individual element A, and (iii) global scattering matrix S with elemental matrices concatenated along the diagonal.

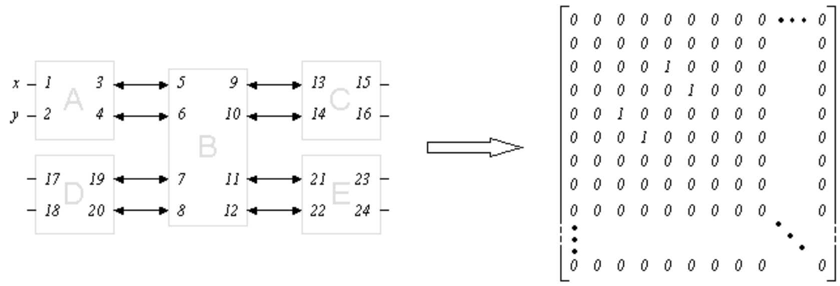

Fig. 3. G-matrix showing only connectivity between the second surface of element A and the first surface of element B.

3. Theory and algorithm

Given the scattering matrix S such that $E_{out} = S\, E_{in}$ (1)

And a connectivity matrix G such that $E_{in} = G\, E_{out} + E_o$ (2)

where Eo is the initial conditions. Substituting equation (2) into equation (1) and eliminating Eout yields

$$E_{out} = S\,(G\, E_{out} + E_o) \quad (3)$$

$$= (S^{-1} - G)^{-1} E_o \equiv H\, E_o \quad (4)$$

The transfer function H relates the output amplitudes E_{out} as a function of the amplitude of the light entering from outside of the system [5], and includes all terms due to multiple reflections and resultant recursive transit through the polarizing elements. If a large matrix H contains redundant or uninteresting terms, such as non-observable variables, it may be reduced in size by the multiplication by a suitable sparse rectangular n×m transformation matrix T and its transpose T^T, reducing H to a more compact m×m size.

$$H = T^T (S^{-1} - G)^{-1}\, T \quad (5)$$

The transfer function matrix H will operate on Jones vectors, and its contents will be complex functions of the optical frequency ω and the physical parameters that are captured in each element's individual one-directional Jones matrix. For the case of monochromatic light, a column vector E_o serves as the optical source term, for example the column vector (1, 0, 0, 0, 0 … 0, 0) would represent unit amplitude launched into the x-polarization of the first port of the first element in the assembly. The observation of the light exiting the p^{th} port is modeled as an ideal square law process, such that for a given port intensity is

$$I_p(\omega) = \int R(\omega)\, H_p(\omega)\, H_p(\omega)^* E_O\, d\omega \quad (6)$$

where R(ω) is the responsivity of the detector, and * indicates the complex conjugate. $I_p(\omega)$ must be evaluated for the two ports representing the x- and y-polarizations corresponding to the surface of interest, and summed, if the detector is polarization-insensitive.

Cross-coupling terms, parasitic terms, functional dependencies (e.g. on manufacturing and material constant tolerances), and optimization strategies readily become apparent by examining term-by-term the above equation. All of the effects of reflection, polarization, attenuation, and optical path length, are explicitly contained in H, and this methodology may be generalized for the case of non-monochromatic light sources and general k-vectors [6]. Besides operations to compute intensity, other operations that may be performed on H include plotting of intensity as a function of some variable, parametric plotting the SOP on the Poincaré sphere [5], optimization operations, calculation of eigen SOP, various figures of merit, embedding [7], statistical analysis with random variables, factorization, state-space techniques [8], etc.

4. Summary and conclusion

A powerful and general simulation technique for complex, folded, and/or re-entrant optical systems is presented, which avoids the burdensome recursive mathematics that arises from multiple reflections. While simple unidirectional systems may be modeled by daisy-chaining Jones matrices together, the $(S^{-1} - G)^{-1}$ formalism permits bidirectional propagation to be modeled in a completely straightforward manner. Any number of reflecting surfaces can be handled by this technique, as can any arbitrary assemblage.

Another value of this approach is the ability to completely separate the effect of subcomponent performance and effect of the geometrical connectivity of the components. This feature is of considerable use in the design phase to evaluate tradeoffs for different topologies and system architectures.

The topologies and complexity of the optical system is limited only by the computational efficiency of the simulation software and amount of evaluation time available to invert large matrices. The trivial example shown in Figure 1 fills a 24×24 matrix, and complex optical fiber systems can easily populate matrices of size > 200×200, making this technique invaluable to zoom in on the parameters of interest in a fairly straightforward manner.

5. References

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