Automated Optical Waveguide Design Based on Wavefront Matching Method

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Abstract: There are large degrees of freedom (DOF) in the design of micro-fabricated optical circuits. This paper introduces the wavefront matching method as an automated design technique of the DOF, and its applications.

1. Introduction

Various optical devices require precise fabrication accuracy, which promotes microfabrication technology with high resolution for optical devices, including optical waveguides, gratings, holograms, etc. Although it enables us to use large degrees of freedom (DOF) in the design of optical circuits, it is difficult to use all of the DOF, because the DOF affect each other and prevent the desired performance from being obtained in the optical circuit design. To overcome the difficulty, many approaches have been proposed, including analog and digital holograms. However, both have disadvantages to realize small devices with the integration of optical functions. The size and functions of analog holograms are physically limited due to the configuration and condition of an optical system for exposing a physical interference pattern. The size and functions of digital holograms are also restricted because the size must be maintained to ignore the finite size of the diffraction element. In addition, most holograms are constructed based on Fourier optics in consideration of a linear system that only takes account of first-order scattering, so the size is large because the circuit is mainly constructed in a region of an almost planar wavefront. In recent years, however, with the drastic growth of the capability of computers, a number of design techniques using large DOF with computational technology, including machine deep learning, have been proposed in which the whole of the DOF is optimized as a solution to the inverse problem [1,2]. The effectiveness of these techniques is mainly verified merely by actual or evaluations of the target performance. Therefore, there remains room for clarifying general characteristics with these techniques (e.g., what is the necessary and sufficient region size or number of parameters, how can we control or suppress the large number of irrelevant DOF, is it possible to interpret the obtained results). Since these points are also further discussed in the field of machine deep learning, it is expected to accelerate the development of optical circuit design technology using large DOF in concert with the field.

In this paper, a technique called wavefront matching method (WFM) is introduced as an automatic design method for optical circuits using large DOF. Characteristics of the WFM are discussed by referring to the above-mentioned items, and recent applications of WFM are introduced.

2. WFM

The WFM is a technique that after studying with the idea of realizing optical circuit generation by numerical calculation using the analogy of the self-forming of optical circuits with photorefractive materials. Photorefractive materials can provide various self-forming optical circuits such as gratings or waveguides, where the refractive index increases according to the light intensity [3]. We used the analogy of self-forming with photorefractive material for the numerical design of optical waveguides, where the refractive index was changed by the numerically simulated optical fields. We found that there is instability in the calculation because of the discreteness of the patterns and the refractive index steps with a large refractive index difference compared to the refractive index change of photorefractive material. In contrast, in the WFM, refractive index changing is determined based on the phases of the optical fields instead of the optical intensities. While this approach cannot be carried out in actual physical systems because no phenomenon exists in which the phase appears explicitly in normal physical systems, in numerical calculation, we can easily use the phase information of the optical fields. The method generates optical circuits and changes the refractive index pattern based on the phase difference between the propagating input optical field and the inverse-propagating output optical field, and it can be regarded as an optimization of the refractive index distribution. In [4], the method was introduced as a steepest descent method based on the variation of the optical field difference between the input and output fields in accordance with an evolution equation derived from the wave equation with a paraxial approximation. Another scheme was proposed in [4], where different evolution equations were set for the input and output fields and the phase difference at the connection was relaxed by changing the refractive index distribution at the interface during alternate propagating in both the forward and backward directions, resulting in optimization of the refractive index distribution. In addition, in [5], the same scheme was expressed by integrating the evolution equation with Suzuki-Trotter decomposition or split-step decomposition. Another expression using the path integral form enables a more physical interpretation. Since it is not in the literature, we include the formula here for later discussion. With an incident space-time point $(x_\mathrm{i}, t_\mathrm{i})$ and a final space-time point $(x_\mathrm{f}, t_\mathrm{f})$,Green's function $\langle x_\mathrm{f}, t_\mathrm{f} | x_\mathrm{i}, t_\mathrm{i} \rangle$ and the variation to the refractive index change at mid-point x_m are described as

$$\langle x_\mathrm{f}, t_\mathrm{f} | x_\mathrm{i}, t_\mathrm{i} \rangle \approx \sum_{\text{all paths, } k_0} \exp\left(i L_\text{path}^{k_0} \right) = \sum_{\text{all paths, } k_0} \exp\left(i \int k_0 n dl_\text{path} \right) , \tag{1}$$

$$\delta \langle x_\mathrm{f}, t_\mathrm{f} | x_\mathrm{i}, t_\mathrm{i} \rangle \propto \sum_{t_\mathrm{i} < t_\mathrm{m} < t_\mathrm{f}, k_0} \underbrace{\langle x_\mathrm{f}, t_\mathrm{f} | x_\mathrm{m}, t_\mathrm{m} \rangle}_{\text{Backword propagation}} i k_0 \delta n (x_\mathrm{m}) \underbrace{\langle x_\mathrm{m}, t_\mathrm{m} | x_\mathrm{i}, t_\mathrm{i} \rangle}_{\text{Forword propagation}}, \tag{2}$$

$$\left(k_0 \text{: Wavenumber in vaccum}, \quad n : \text{Refractiveindex}, \ L_\text{path}^{k_0} : \text{Optical path length}, \quad l_\text{path} : \text{Path length} \right),$$

where it should be noted that Eq. (2) can be trivially obtained thanks to the path integral form. While in most WFM applications, the beam propagation method (BPM), which ignores the back-reflection, has been adopted as the numerical calculation scheme, as described in [5], the above formulation enables applying the numerical calculation schemes considering light propagation including back-reflection for WFM. For example, in the frequency domain, Eq. (2) can be transformed into a point-wise equation while omitting the symbol regarding frequency and without compromising propagation including back-reflection as

$$\delta \langle x_\mathrm{f} | x_\mathrm{i} \rangle \propto \underbrace{\langle x_\mathrm{f} | x_\mathrm{m} \rangle}_{\substack{\text{Backword} \\ \text{propagation}}} i k_0 \delta n (x_\mathrm{m}) \underbrace{\langle x_\mathrm{m} | x_\mathrm{i} \rangle}_{\substack{\text{Forword} \\ \text{propagation}}}. \tag{3}$$

Moreover, using Eq. (3), the finite difference time domain (FDTD) method or finite element method (FEM) can be applicable numerical calculation schemes for WFM, as well as BPM. The path integral expression is also useful to investigate the characteristics of WFM. Table 1 shows example characteristics of WFM regarding general aspects mentioned as examples in Section 1. The dependency of performance on region size can be roughly estimated to be exponential ignoring degradation by interference, because the performance of optical circuits depends on the expression capacity of the system given by the connection via optical paths. To suppress the large number of irrelevant DOF for waveguide-type optical circuits, a constraint condition of the change of the refractive index distribution is usually introduced, such as a constraint of the change on the waveguide wall, which has been adopted for various applications of optical waveguides using WFM [512]. Since the performance of an optical circuit is governed by the interfering optical paths, as shown in Eq. (1), the interpretability of an optical circuit generated by WFM is given by the context of interfering optical paths. For example, as shown in Section 3, the wavelength dependency of optical circuits generated by WFM is suppressed compared to conventional circuits. This is because the wavelength change corresponds to the change of the global refractive index value in Eq. (3), and when the refractive index value is extreme, the wavelength can be interpreted as an extreme value for Eq. (3), or it introduces insensitivity to the optical circuit system.

Table 1. Example Characteristics of WFM

Items	Characteristics of WFM
1) Dependency of performance on region size	Potentially exponential
2) Controlling irrelevant DOF	Useful constraint thanks to point-wise condition
3) Interpretability	Using context of interfering optical paths

3. Applications and Prospects of WFM

Although WFM is applicable for general light propagation including back-reflection as described in Section 2, WFM has been adopted to design relatively large optical devices using BPM compared to optical circuits using Si photonics, because large optical devices can be analyzed only by BPM and WFM is well suited for using BPM. In the early days, WFM was applied to improve the optical performance of silica planar lightwave circuits (PLCs), such as low-crosstalk and low incidence-angle cross waveguides, low-loss Y-branch circuits [5], and loss reduction of arrayed waveguide gratings [6]. These are simple optimizations in the sense that they use well-defined targets, such as the reduction of insertion loss. Subsequently, WFM was adopted for widening the wavelength pass band for several applications, including the first high contrast refractive index optical waveguide application [7], a shorter wavelength domain application [8], and a visible light application [9]. All of these seem to use the nature of the correspondence between the wavelength and refractive index in Eq. (3) described above as well as the multiple wavelength setting. Propagation modes are an important property of light that can be controlled by the waveguide structure, but the relation is not obvious. Several applications have been proposed for mode multiplexing communications [10] and lossless power couplers using single-mode-multi-input to multimode transformation [11]. Recently, WFM using a numerical calculation scheme of FEM and WFM condition for vectorial fields were proposed, and the method was successfully applied to a very high contrast waveguide in which the backward reflection had to be considered [12]. Another recent study in a different direction used large-scale optimization for multi-plane spatial mode modulation [13]. This suggests that WFM has high affinity for spatial optics, because the point-wise condition of WFM provides simple and effective computation of limited areas, such as spatial light modulators or surfaces of optical elements.

Recently, several deep neural network architectures using optics have been proposed [14], and the error-back-propagation method in the learning process seems to be similar to WFM. In addition, the analysis of the residual networks, which are familiar and high performance deep neural networks, in [15] seems to indicate that there is a similarity between the overlay networks of the ensembles and optical circuits and therefore the techniques or the interpretations of the performances, such as in Table 1, could be shared. Moreover, the possibility of computation utilizing waves has been suggested [16]. As noted in [4], we can expect to develop WFM further by using similarities or sharing ideas and techniques for each type of deep machine learning and optical circuit using DOF or WFM.

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