Inverse Design of a Terahertz Quantum Algorithm Emulator

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Abstract: A metastructure-based on a graded-index lens is presented for the terahertz regime as an emulator for quantum algorithms. Further optimization is presented by applying machine learning in an inverse design strategy.

1. Introduction

Optical computers perform computation with photons as opposed to the more traditional electron-based computing architecture. Advantages include the use of multiple frequencies, higher speed, higher efficiency, and lower power consumption. [1]. These favorable characteristics further the interest in metamaterials as good candidates for quantum information processing [2]. We propose a metastructure of flexible polyimide for the gradient index (GRIN) lens that functions in the terahertz regime to realize the Deutsch-Jozsa (DJ) algorithm. The DJ algorithm is considered as one of the first examples of quantum algorithms that is exponentially faster than any possible deterministic classical algorithm [3–5]. In the DJ problem, an oracle block implements a binary function f. The function f takes n-bit binary values as input and produces either 0 or 1 as output. If the value of f is 0 on all outputs or 1 on all outputs, f is called constant function. However, if the value of f is 1 for half of the output domain and 0 for the other half, f is called a balance function. The oracle sub-block encodes the detecting function f(y) by assigning a phase shift on each spatial position along the axis of wave propagation while the GRIN lens sub-block (length of l) acts as a Fourier transformer to evaluate the output signal [6]. These two components make up the quantum algorithm emulator (QAE) as shown in Fig. 1(a).

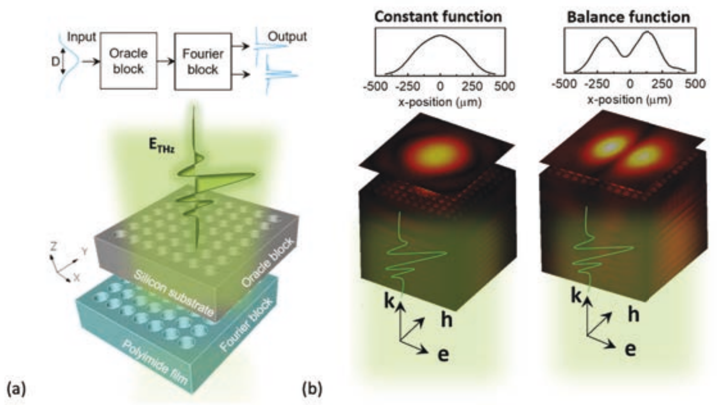

Fig. 1. (a) Metamaterial-based multilayer configuration of the Deutsch-Jozsa algorithm emulator. (b) Electric field intensity maps at the focal plane of the GRIN lens for 0.8 THz frequency, with the detecting function being constant and balance, respectively.

2. Materials and Methods for Numerical Simulations

The aperture size of the lens is about 1 mm with a refractive index profile designed by altering the geometric parameters in each individual unit cell of dimension 70 μm x 70 μm x 127 μm. When the incident light irradiates the surface of the oracle block, the phase of the transmitted wave is modulated with a factor $k_0 n(y) d_0$, where $k_0 = 2\pi/\lambda_0$ is the vacuum wave vector, d_0 is the thickness of the oracle block and $n(y)$ is the effective refractive index at position (y). The detecting function $f(y)$ is encoded into the input states by assigning a phase modulation on each spatial position (y) along the input transversal direction. The refractive index of the oracle operator is designed to achieve either 0 or π phase distribution depending on the value of the function f. To evaluate the performance of the device, we performed numerical simulations based on the finite-difference time-domain (FDTD) method. Fig. 1(b) shows the electric field intensity maps at the focal plane of the GRIN lens with the detecting function being constant and balance, respectively. The maximum intensity at the y = 0 position means the encoded function $f(y)$ is constant. Conversely, if the center intensity is at a minimum and the intensity of this same output electric field is not symmetric, this implies a balanced function.

3. Materials and Results for Machine Learning Optimization

To further verify our structure parameters, a machine learning (ML) based optimization procedure is implemented into the design of the GRIN lens [7] as shown in Fig. 2(a). First, the data for training the proposed neural network (NN) model is generated using numerical simulation software. The geometric configuration is randomly generated using MATLAB with the constraints on r_i and h, respectively. The constraints for r_i are $0 < r_i < a/2$ and $r_1 < r_2 < r_3 < r_4 < r_5 < r_6$ where $a = 70\mu m$ is the characteristic length of the unit cell of each hole. The constraint of h is $50\mu m < h < 300\mu m$. To optimize the performance of the GRIN lens, the holes on the surface were divided into six groups from inner to outer ring with the radius of r_1, r_2, r_3, r_4, r_5, and r_6, respectively. After training with 100 iterations, the proposed model can precisely predict the geometric configuration from $(\bar{v}_{out})$. Hence, we can feed the model with the desired $(\bar{v}_{in})$ so that the optimal geometric configuration $(\bar{v}_{out})$ is achieved and verified numerically. According to Fig. 2(b), the optimized structure performs much better than the initial design.

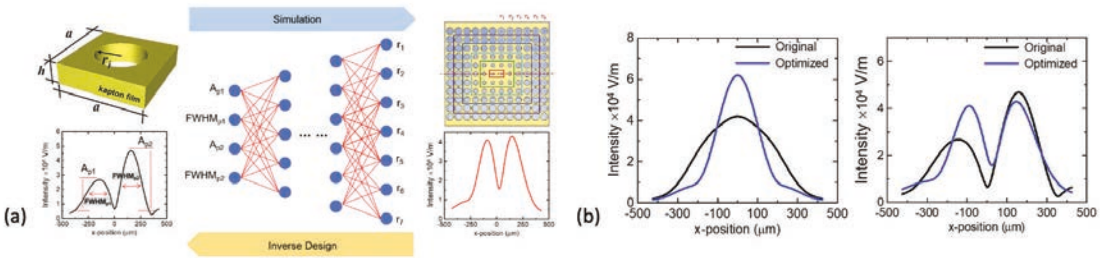

Fig. 2. (a) The schematic of the proposed ML-based optimal model (b) The performance comparison of the initial and optimal design for (left) all-zero all-one case and (rigt) half-zero half-one case.

4. Conclusion

We propose a metastructure of an all dielectric, flexible polyimide for a GRIN lens that functions in the terahertz regime as part of a QAE to realize the DJ algorithm. Using a ML based optimization procedure, the original design of the GRIN lens was improved to enhance the output signal of the wave incident to the QAE structure.

Acknowledgment

A portion of this work was supported by the Co-design Center for Quantum Advantage (C2QA) under contract number DE-SC0012704 and ABW would like to thank the GEM Fellowship for financial support.

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