Optimal design of NRD guide devices using 2D full-vectorial finite element method

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LETTER

Optimal design of NRD guide devices using 2D full-vectorial finite element method

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Abstract In this paper, we propose an optimal design approach based on a concept of mosaic-like structure for achieving high performance NRD devices. In order to improve design efficiency, we employ the recently proposed two-dimensional full vectorial finite element method (2D-FVFEM) which can accurately model 3D structure of NRD as a numerical simulation method. As an optimization method, we employ either direct binary search (DBS) algorithm or genetic algorithm (GA) depending on design problems. In order to show the usefulness of our approach, design examples of crossing and T-branch waveguides are considered and high transmission efficiency greater than 99.9% for crossing waveguide and 49.8%:49.8% for T-branch waveguide is achieved. The numerical results by 2D-FVFEM are verified by 3D-FVFEM.

Keywords: non-radiative dielectric waveguide (NRD guide), mosaic-like structure, direct binary search (DBS) algorithm, genetic algorithm (GA), finite element method (FEM), full-vectorial analysis
Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Non-radiative dielectric waveguide (NRD guide) [1] is considered a promising platform because compact millimeter-wave circuits can be found thanks to their non-radiative nature. The NRD guide has attracted much attention since Yoneyama et al. proposed it, and various NRD guide devices in the millimeter-wave band have been proposed [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. In general, NRD guide supports two orthogonal modes referred to LSM_{01} and LSE_{01}, as shown in Fig. 1. These modes may couple with each other in non-uniform parts of the circuit configuration and this coupling tends to degrade performance of NRD guide devices. Therefore, careful design has to be required in designing high performance and compact circuit components.

In recent years, several optimal design approaches for dielectric waveguide devices have been intensively developed in photonics [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31]. These optimal design methods

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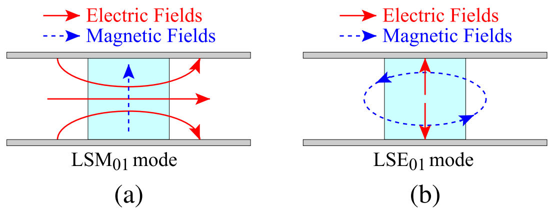

Fig. 1 Non-radiative modes in NRD guide. (a) LSM_{01} and (b) LSE_{01} mode.

have a potential to find high performance devices with novel unique structures that we have never thought of before. Although NRD guides are dielectric waveguides like optical waveguides, unlike optical waveguides, NRD guides have a structure in which a dielectric waveguide is sandwiched between two metal plates to realize non-radiative nature. Thus, it is crucial to develop efficient optimal design approach for NRD guide devices. In topology optimal design approach which has high design flexibility, in general, a huge number of numerical simulation has to be required. Therefore, extremely long computational time has been required in the design of 3D waveguide devices. Recently, we newly developed two-dimensional full-vectorial finite element method (2D-FVFEM) for NRD guide devices [32]. This simulation technique can rigorously calculate transmission properties of NRD guide devices with 3D structure in 2D space, thus, computational effort can be greatly reduced in an optimal design approach.

In this paper, we develop an efficient optimal design approach for NRD guide devices based on a concept of mosaic-like structure. In order to design dielectric waveguide devices, various numerical expressions in design region have been proposed. Among them, the concept of mosaic-like structure is one of attractive design approaches. In the design of mosaic-like structure in photonics, out-of-plane loss may sometimes degrade device performance. On the other hand, in NRD guide devices, out-of-plane radiation and in-plane radiation are essentially prohibited, then, this concept is thought to be more suitable for design of NRD guide devices. In our design approach, 2D-FVFEM for NRD guide is employed as a numerical simulation technique and the direct binary search (DBS) algorithm [29] or genetic algorithm (GA) [16] is employed depending on design problems. In order to show the usefulness of our approach, design examples of crossing and T-branch waveguides are considered are shown. The frequency characteristics of devices designed by 2D-FVFEM are verified by 3D-FVFEM.

2. Implementation of optimization algorithms

2.1 Numerical expression in design region

We consider a design model as shown in Fig. 2. The aim of our optimal design is to obtain optimal structure with desired outputs when fundamental LSM_{01} is launched into port 1. For this purpose, a structure in design region is expressed by numerical design variables and those values are optimized. In this paper, we employ the concept of digital material. The design region is expressed as a grid pattern as shown in Fig. 2 and the material in each pixel is a dielectric or air. We optimize this gird pattern by using DBS algorithm or GA. DBS algorithm is a simple approach, easily to be implemented, and sometimes efficiently provide an optimal structure. However, DBS is not guaranteed to give a globally optimal solution. In order to offer more versatile design, we also employ GA.

2.2 Direct binary search algorithm

The DBS algorithm is often used in design of photonic devices because of its easiness of implementation [29]. In the DBS algorithm, an initial structure is generated in some way and one pixel is randomly selected and inverted. This change is retained if the device performance is improved, otherwise, the pixel is restored. This operation is performed on all the pixels in a random order. One iteration is defined as the completion of the operation on all pixels. This iteration is repeated until the desired property is obtained or the property is no longer improved.

2.3 Genetic algorithm

GA is more versatile design approach than DBS and is applied to various optimization problems. Although various version of GA is developed, we employ a standard GA algorithm [16]. First, some individuals with random grid pattern are generated and these individuals evolve based on genetic operation, such as selection, crossover, and mutation. In this paper, we employ both elite selection and ranking selection as a selection scheme. In each generation, only one best individual is saved by elite selection and the other individuals are generated by uniform crossover of two parent individuals selected by ranking selection. After that, all the individuals except for elite individual may mutate with a predetermined probability. This change of generations is repeated until the desired property is obtained or the property is no longer improved.

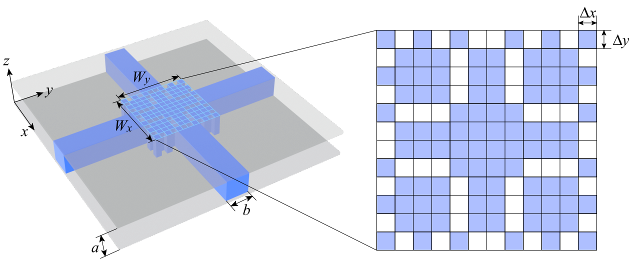

Fig. 2 Design model based on mosaic-like structure.

3. Numerical examples

In order to show the usefulness of our design approach, we demonstrate two design examples of NRD guide devices. In the following design examples, we assume the metal plate separation is $a = 2.25$ mm, the dielectric strip width is $b = 2$ mm, and the relative permittivities of the dielectric and air are $\varepsilon_r = 2.2$ and $\varepsilon_{air} = 1$, respectively. Furthermore, LSM_{01} mode operation around 60 GHz is considered and incident port is set to be port 1.

3.1 Crossing waveguide

In order to show the potential of our optimization approach, first, a low crosstalk crossing-waveguide is designed by using DBS algorithm. The design setup and optimized structure of NRD crossing waveguide is shown in Fig. 3. The structural parameters are set to be $d_{PML} = 5$ mm, $l = 10$ mm and $W_x = W_y = 6$ mm. The design region is discretized into 12×12 pixels with size of 0.5 mm $\times\, 0.5$ mm. Utilizing structural symmetry, only the pixels in one-eighth region surrounded red line (21 pixels) are designed. The material in each pixel has been optimized by DBS approach in just 10 iterations. In this numerical example, we targeted the maximum power transmission from input port to output port, when LSM_{01} mode at frequency of 60 GHz is launched into input port 1. The steady-state propagation field in the non-optimized structure and the optimized structure are shown in Fig. 4. The transmission efficiency is 99.9 % in the optimized crossing waveguide compared with that of 61.0 % in the non-optimized one. We can see that clearly in Fig. 4 the optimized structure greatly suppresses the reflection and

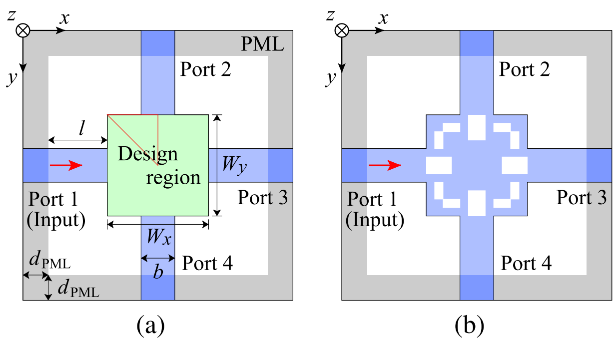

Fig. 3 (a) Design model of crossing waveguide and (b) its optimized structure.

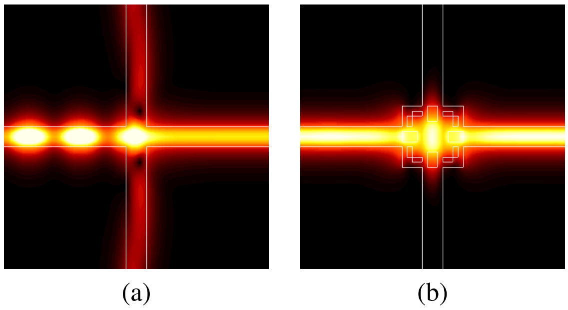

Fig. 4 Propagation field in NRD crossing waveguide (a) non-optimized structure (b) optimized structure.

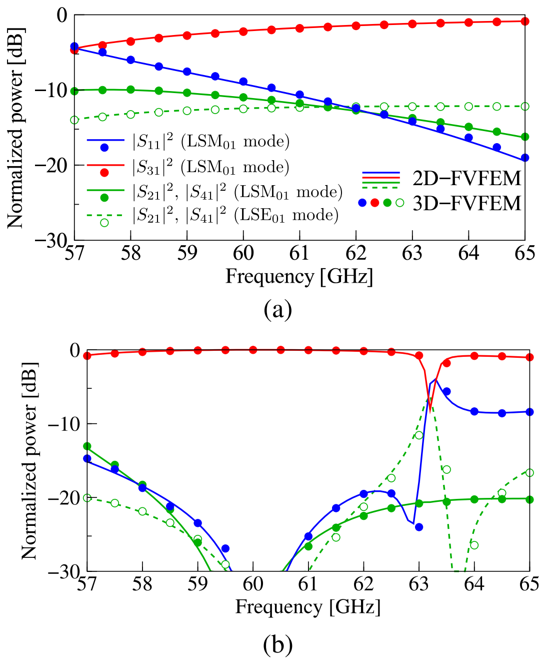

Fig. 5 The normalized powers of (a) non-optimized and (b) optimized NRD crossing waveguide.

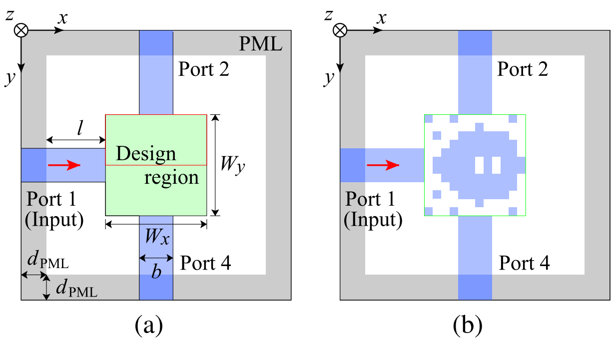

Fig. 6 (a) Design model of T-branch and (b) its optimized structure.

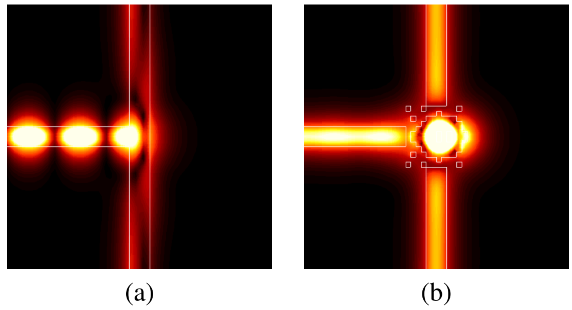

Fig. 7 Propagation field in NRD T-branch waveguide (a) non-optimized structure (b) optimized structure.

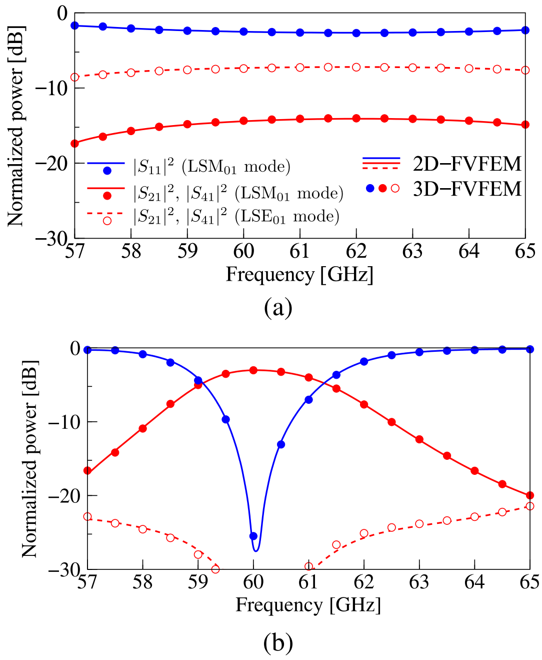

Fig. 8 The normalized powers of (a) non-optimized and (b) optimized NRD T-branch waveguide.

crosstalk effect than the non-optimized one. Furthermore, the frequency characteristics of the non-optimized and optimized crossing waveguides are shown in Fig. 5. Numerical results of those devices calculated by 3D-FVFEM are also shown. The designed approach realized the device structure with the remarkable transmission characteristics and practical design specifications. Figure 4 shows that the NRD guide can be intersected on a planar circuit. It has the potential to further miniaturize the NRD guide circuit.

3.2 T-branch waveguide

Next, we designed a T-branch waveguide to split the input power equally into two output ports. The structural parameters and incidence condition are the same as considered in the previous example. Fig. 6 shows the design setup of the T-branch waveguide and the optimized structure. The number of pixels to be optimized is 72 considering the structural symmetry. In this design, we applied GA for the optimization of structure in the design region because the DBS approach does not obtain a structure satisfying the desired output. We achieved the optimized structure and desired results in just 50 iterations with 64 population size. The propagation fields of the non-optimized and the optimized structures are shown in Fig. 7. The transmission efficiency at both output ports is 3.5 % : 3.5 % and 49.8 % : 49.8 %, respectively. The frequency characteristics of the optimized and the non-optimized structures are shown in Fig. 8. Numerical results of those devices calculated by 3D-FVFEM are also shown. Due to superior performance, it is confirmed that the T-branch guide optimized by GA meets the practical performance requirement.

4. Conclusion

In this study, we demonstrated the usefulness of design approach of NRD guide devices with mosaic-like structure using DBS algorithm and GA. We coupled the originally developed 2D-FVFEM with optimization algorithms for the efficient design of NRD guide devices. Actually, in this study, we investigated the optimization algorithms for NRD guide devices and their effectiveness on the transmission characteristics. We confirmed that the proposed design approaches are able to efficiently design compact NRD based waveguide devices with excellent transmission performance. In addition, we also characterized the proposed devices and numerically demonstrated transmission efficiency of the crossing-waveguide is 99.9 % and T-branch guide is 49.8 % : 49.8 % at both output ports. The numerical results by 2D-FVFEM are verified by 3D-FVFEM. The transmission efficiency of both NRD guide devices is superior to that of non-optimized ones. Our proposed design approach is applicable to design other integrated NRD based guide devices and also contributes to increase the device functionality.

Acknowledgments

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