Design of a GaN-Based 1x2 Optical Power Splitter Using Rectangular Waveguide Coupling

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Abstract

The need for compact and efficient optical power splitters is becoming increasingly urgent due to the growing demand for integrated photonic devices, which are essential in fields like optical interconnects and sensing. This study addresses the issue by focusing on the design and analysis of a GaN based 1x2 optical power splitter that employs rectangular waveguide coupling. The primary aim of the research is to evaluate how the number of rectangular waveguide couplings affects the performance of the power splitter, particularly in terms of splitting angle and excess loss. To achieve this, simulations were conducted using the finite-difference time-domain (FDTD) method. The design was tested with three configurations: three, five, and seven rectangular waveguides. The research design follows a structured simulation approach, where the FDTD method was employed to explore the impact of varying the number of rectangular waveguides. The process involves systematically altering the number of coupling sections and analyzing the resulting output. The 3D optical power distribution and the optical field intensity at the splitter output for each design were examined. Additionally, the excess loss distribution over the wavelength range of 1500 nm to 1600 nm was determined, demonstrating the potential of the proposed designs for optical communication applications. This data analysis enabled the researchers to evaluate the performance of each configuration. Notably, as the number of waveguides increased, the splitting angle became wider, but this was accompanied by a rise in excess loss. These findings demonstrate the potential of the proposed design for practical applications. Future studies could explore further optimization and real-world implementation.

Keywords: GaN, Optical power splitter, coupling, rectangular waveguide.

I. Introduction

The rapid advancement of photonic integrated circuits (PICs) has heightened the need for compact, efficient, and reliable optical components that can be seamlessly integrated into a variety of optoelectronic devices. Optical power splitters, which split an optical signal into multiple paths, are among the key components in such systems, playing a critical role in applications ranging from optical communication networks to sensing and signal processing[1-4]. The 1x2 optical power splitter, a fundamental building block in PICs, can be designed using various waveguide structures[5-10]. Symmetrical 1x2 power splitters equally distribute optical power and are used in designs like Y-branches, multimode interferometers (MMI), and rectangular waveguides coupling[11]. Rectangular waveguides coupling, in particular, offer a flexible platform for integrating power splitters into PICs. The coupling mechanism between adjacent waveguides is a critical factor in determining the efficiency and effectiveness of the power splitting process[8].

Gallium Nitride (GaN) has emerged as a highly promising material for photonic applications due to its wide bandgap, high electron mobility, and excellent thermal stability[12-14]. These properties make GaN-based devices particularly well-suited for high-frequency and high-power applications, as well as for integration into harsh environments[15]. GaN-based devices have been developed for applications as waveguides, including couplers[16], demultiplexer[17], modulators[18], bragg reflectors[19], waveguide intersection[20], and optical power splitters[7]. Leveraging GaN in the design of optical components such as power splitters offers potential benefits, including enhanced performance and durability[18]. Sapphire is well known for its mechanical and thermal stability, high refractive index, and transparency across a wide spectral range[21, 22].

The design and analysis of a GaN-based 1×2 optical power splitter employing rectangular waveguide coupling are presented in this study. Our approach focuses on optimizing waveguide dimensions and coupling parameters to achieve efficient power splitting with minimal insertion loss across different angle width variations. We employ numerical simulation techniques to evaluate the splitter's performance, considering key metrics such as power distribution and wavelength sensitivity. The findings of this research contribute to the ongoing development of GaN-based photonic devices by providing a practical design framework for integrating high-performance optical power splitters into PICs. This work not only demonstrates the feasibility of GaN in advanced photonic applications but also sets the stage for future innovations in the field of integrated optics.

II. METHOD

A. Wave Propagation

The wave propagation in this study was simulated using the Beam Propagation Method (BPM), which is commonly employed to model the evolution of optical fields in waveguides and photonic devices. BPM is based on the paraxial approximation of the Helmholtz equation. The electric field distribution $E(x, y, z)$ along the propagation direction z is described by the scalar wave equation:

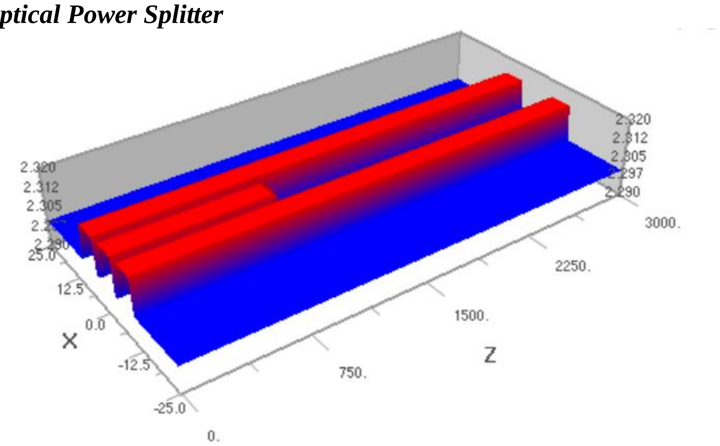
$$\frac{\partial^2 E}{\partial x} + \frac{\partial^2 E}{\partial y} + k_0^2(x, y, z)E = \frac{\partial^2 E}{\partial z} \tag{1}$$

where k_0 is the free-space wavenumber, and $n(x, y, z)$ is the refractive index distribution. For computational efficiency, BPM uses the paraxial approximation, which assumes that the field varies slowly in the z-direction. This allows the wave equation to be simplified into the paraxial form:

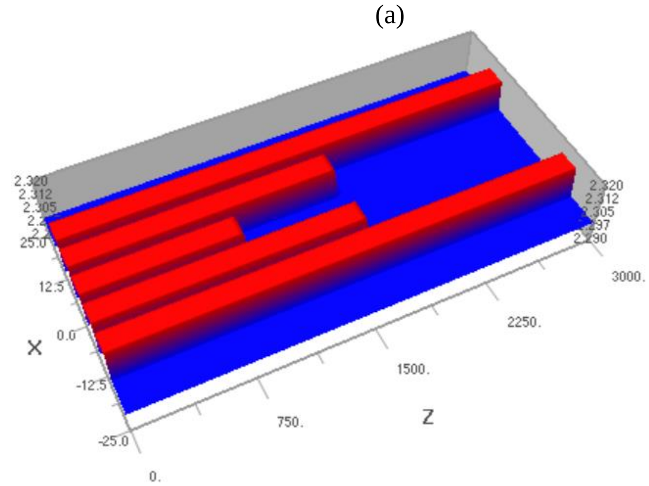
$$\frac{\partial^2 E}{\partial z} = \frac{i}{2k_0}\left(\frac{\partial^2 E}{x^2} + \frac{\partial^2 E}{y^2}\right) - ik_0(n(x, y, z) - n_0)E \tag{2}$$

where n_0 is the reference refractive index. The equation is solved iteratively along the z-direction, with the electric field updated at each step using the split-step Fourier method.

B. The Proposed Optical Power Splitter



(a)



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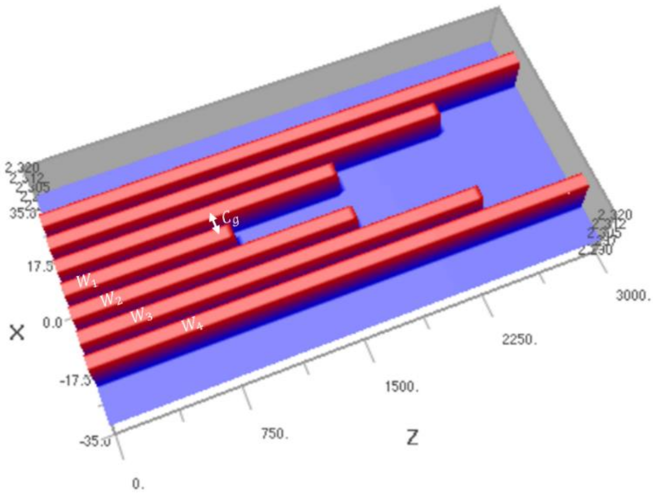

(c)

Figure 1 The Proposed 1x2 Optical Power Splitter with (a) Three, (b) Five, and (c) Seven Rectangular Waveguides

The rectangular waveguide was constructed with carefully selected dimensions to support single-mode operation at the target wavelength. Figure 1 shows the proposed optical power splitter design with seven rectangular waveguides. We proposed 1x2 optical power splitter utilizing varying number of rectangular waveguides, specifically three, five, and seven. L is the length of the input waveguide W_1 and L_2, L_3, L_4 are the length of waveguide W_2, W_3, W_4 respectively. The coupling gap is defined as C_g.

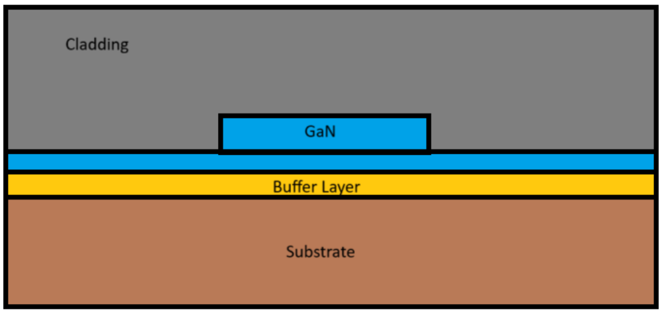

Figure 2 The structural layer of the waveguide

The refractive indices of GaN and sapphire were set according to known material properties, with GaN having a higher refractive index than sapphire with a refractive index of 2.314 and 1.76 respectively, allowing for effective optical confinement in the core. The structure of the waveguide is shown in Figure 2.

C. Operating Principle

The power transfer between the coupled waveguides was simulated to analyze the performance of the splitter. Initially, light was launched into one waveguide (denoted as waveguide 1), and the transfer of power to the adjacent waveguide (waveguide 2) was monitored as a function of the propagation distance z. The power in each waveguide was calculated using the following relationships:

$$P_1(z) = P_0 cos^2(\kappa z) \quad (3)$$

$$P_2(z) = P_0 sin^2(\kappa z) \quad (4)$$

Where $P_1(z)$ and $P_2(z)$ represent the optical power in waveguides 1 and 2, respectively, at a distance z, and P_0 is the total input power initially launched into waveguide 1.

The coupling length L_c, defined as the distance over which complete power transfer occurs from one waveguide to the other, was a critical parameter in our design. The coupling length is inversely related to the coupling coefficient κ and is given by:

$$L_c = \frac{\pi}{2\kappa} \quad (5)$$

At $z = L_c$, the optical power initially in waveguide 1 is entirely transferred to waveguide 2, demonstrating maximum coupling efficiency. By optimizing the coupling length, we ensured that the power splitter achieved efficient and balanced power distribution across its output ports.

Key parameters influencing mode coupling, such as waveguide separation, refractive index contrast, and operating wavelength, were systematically varied to optimize the splitter's performance. The waveguide separation was adjusted to control the coupling strength κ, while the refractive index contrast between the GaN core and sapphire substrate influenced the confinement of the optical modes and, consequently, the coupling efficiency.

III. Results and Discussion

The numerical experiment was conducted using OptiBPM. We investigated the effects of varying the waveguide width within the range of 2 µm to 6.5 µm and thickness within the range of 2 µm to 6.5 µm. The results indicate that a waveguide width and thickness of 5 µm yielded the highest relative optical power among the three proposed designs. To determine the length of the waveguides, we used analytical calculations of the coupling and coupling coefficient. Our analytical calculation indicates that the optimal lengths for the waveguides in seven rectangular waveguides configuration are as follows: 1000 µm for waveguide 1, 1700 µm for waveguide 2, 2400 µm for waveguide 3, and 3000 µm for waveguide 4.

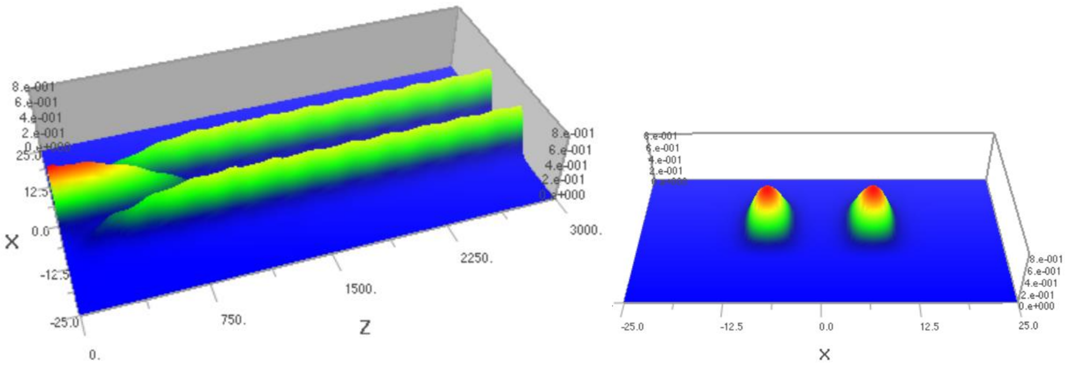

Figure 3 3D Optical Power Distribution and Optical Intensity Field Distribution at z = 3000 µm of the Proposed Design with Three Rectangular Waveguides

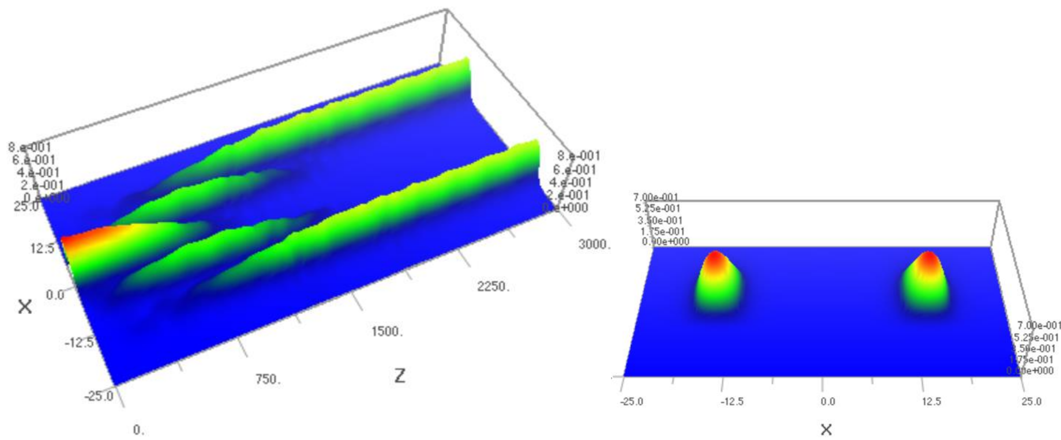

Figure 4 3D Optical Power Distribution and Optical Intensity Field Distribution at z = 3000 µm of the Proposed Design with Five Rectangular Waveguides

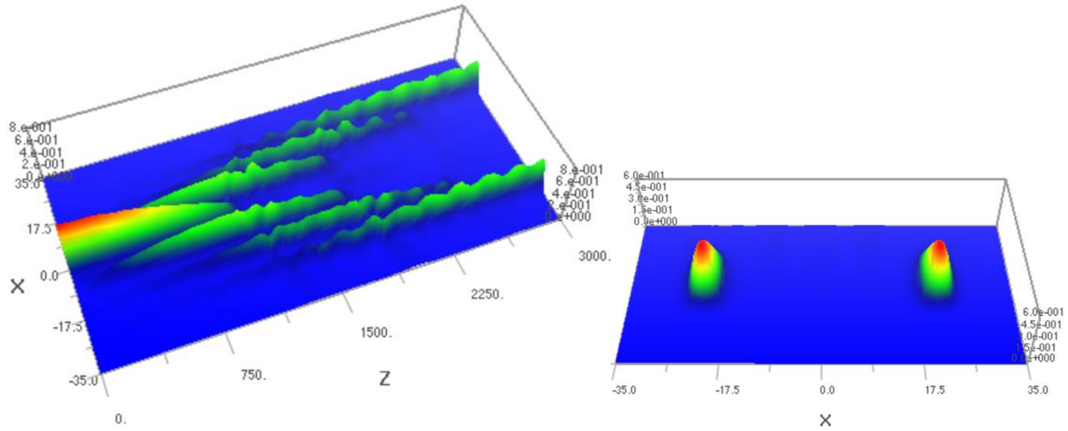

Figure 5 3D Optical Power Distribution and Optical Intensity Field Distribution at z = 3000 µm of the Proposed Design with Seven Rectangular Waveguides

The 3D image of the optical field distributions and optical intensity field distributions of the proposed design with three, five, and seven rectangular waveguides were shown in Figure 3, Figure 4, and Figure 5 respectively. The optical power reached its peak at x = -7 µm and x = 7 µm, x = -14 µm and 14 µm, x = 20 µm and x = 20 µm for design with three, five, and seven rectangular waveguides respectively. The performance of the 1x2 optical power divider is described by the excess loss at the output ports. The excess loss, which represents the power lost due to the reflective and absorptive properties of the material, has been calculated. The calculations of this excess loss were carried out as follows:

$$Excess\ Loss = -10log\left(\frac{P_{out}}{P_{in}}\right) \quad (6)$$

where, P_{out} refers to the total optical power at the two output ports, while P_{in} represents the total optical power at the input port.

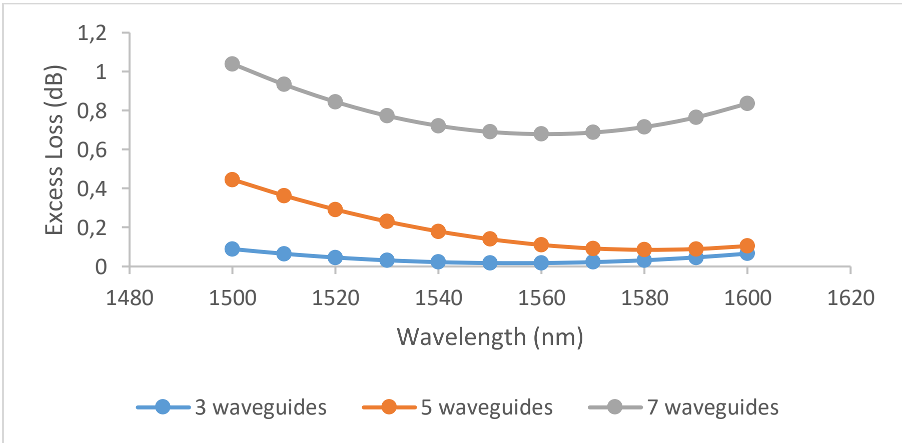

Figure 6 The excess loss for the wavelength range from 1500 nm to 1600 nm

By using Equation 6, the excess loss values in the wavelength range of 1500 nm to 1600 nm were obtained. The values in this wavelength range indicate its potential use for optical communication, and their distribution can be seen in Figure 6. The proposed design of 1 x 2 optical power divider with three rectangular waveguides yields the lowest excess loss at a wavelength of 1550 nm with a separation width of 14 µm. This configuration is optimal for applications prioritizing minimal power loss. The design with five rectangular waveguides achieves the lowest excess loss at 1580 nm with a separation width of 28 µm and suitable for scenarios requiring both efficiency and wider splitting angle. The design with seven rectangular waveguides shows the lowest excess loss at 1560 nm with a separation width of 40 µm and serves applications where splitting angle outweighs power efficiency. Although the three rectangular waveguides design results in the lowest excess loss, it produces a smaller splitting angle. In contrast, the seven waveguides design has a higher excess loss but a larger splitting angle. Increasing the number of waveguides used for coupling generally results in greater power losses at each coupling point.

GaN's wide bandgap and high refractive index contrast with sapphire were pivotal in achieving effective optical confinement and robust performance across the wavelength range of 1500 nm to 1600 nm[23-25]. The splitter's excess loss varied across the wavelength range, reflecting the wavelength sensitivity inherent in photonic devices. Optimization of waveguide dimensions and coupling gaps contributed to minimizing these losses. Given the results, the three-waveguide configuration is recommended for applications emphasizing efficiency, such as low-power optical communication networks. Conversely, the seven-waveguide design is more suitable for high-power applications requiring broader angular coverage, such as optical sensing arrays.

IV. CONCLUSION

In this study, three different designs of a 1x2 optical power splitter using waveguide coupling methods were developed, each employing three, five, and seven rectangular waveguides. Power splitting occurs through power transfer between adjacent waveguides. The 3D optical power distribution and optical field intensity distribution at z = 3000 µm were analyzed for the three designs. The separation widths at the splitter output for the three designs were found to be 14 µm, 28 µm, and 40 µm for the designs with three, five, and seven rectangular waveguides, respectively. The distribution of additional optical power loss across the wavelength range of 1500 nm to 1600 nm was also obtained, demonstrating that the proposed designs are suitable for optical communication applications. The design with three rectangular waveguides exhibited the lowest additional loss and the smallest splitting angle, making it suitable for applications prioritizing minimal power loss, whereas the design with seven rectangular waveguides produced a larger splitting angle at the expense of higher additional loss.

This study makes a significant contribution to the field of optical communication by presenting a comparative analysis of optical power splitters with varying numbers of waveguides, providing insights into their performance for optical communication systems. The study highlights the trade-off between minimizing additional loss and achieving a larger splitting angle, offering valuable data for optimizing optical device designs. However, the observed increase in power loss with the addition of waveguides poses a challenge to the scalability of such designs. Future research should explore advanced materials with lower intrinsic losses or innovative waveguide structures capable of reducing additional loss in designs with multiple couplings. Furthermore, integrating these optimized designs into practical photonic systems, such as optical sensor arrays or next-generation communication networks, could further validate their effectiveness and uncover additional performance improvements.

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