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1 × 4 MMI visible light wavelength demultiplexer based on a GaN slot-waveguide structure

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ABSTRACT

High transmission losses are the key problem that limits the performance of visible light communication systems, which work on wavelength division multiplexing (WDM) technology.

To overcome this problem, we propose a novel design for a 1 × 4 optical demultiplexer based on the multimode interference in a slot-waveguide structure that operates at 547 nm, 559 nm, 566 nm, and 584 nm. Gallium nitride and silicon oxide were found to be excellent materials for the slot-waveguide structure. Simulation results showed that the proposed device can transmit four channels that work in the visible light range with a low transmission loss of 0.983–1.423 dB, crosstalk of 13.8–18.3 dB, and bandwidth of 1.8–3.2 nm. Thus, this device can be very useful in visible light networking systems, which work on the WDM technology.

1. Introduction

The growing needs in the visible light communication (VLC) systems require [1–3] new and powerful waveguide components that can support high-speed light communication with low transmission losses.

Demultiplexers are an important part of optical communication networks and can be implemented using several techniques: multimode interference (MMI) couplers [4,5], Y-branch devices [6], and Mach-Zehnder interferometers [7].

A slot-waveguide structure is composed of a narrow low-index region surrounded by two layers of a high-index material [8]. This structure allows light to be strongly confined and guided through it [9] due to the total internal reflection effect [10].

MMI devices are commonly implemented in photonic integrated circuits due to their low loss, large optical bandwidth, and simple structure [11–15]. Self-imaging is an effect that occurs in waveguides due to MMI, by which the electric field profile that enters the device is duplicated into one or more images (depending on the geometry of the MMI) along the propagation axis of the device at periodic intervals [15].

GaN is a promising material for high-power and high-temperature electronics due to its wide energy band gap and high critical electric field [16]. Recently, researchers assessed the performance of GaN-based slot-waveguide device and found it suitable for transmitting visible light with 0.1–0.4 dB/cm transmission loss [17].

Moreover, researchers show the great potential of using a silicon (Si) slot-waveguide-based MMI structures for designing splitters [18,19,20] and wavelength demultiplexers in the C-band range [12,21]. However, Si slot-waveguide is not suitable for transmitting light in the visible range because Si has a high absorption loss. To overcome this problem, we propose to use GaN-SiO_2 slot-waveguide that enables the transmission of visible light without confinement losses.

In this paper, a design of a 1 × 4 wavelength demultiplexer based on multimode interference in a GaN– SiO_2 slot-waveguide structure, which divides four channels in the visible light range, is presented. The selected wavelengths were found to be 547 nm (λ_1), 559 nm (λ_2), 566 nm (λ_3), and 584 nm (λ_4).

The device is based on the cascading of three 1 × 2 MMI couplers, six S-bands, six output tapers, and one waveguide segment. The geometrical parameters of the MMI couplers and the slot-waveguide structure were analyzed to obtain a strong field confinement and to find the optimal lengths of the MMI couplers. The simulations were carried out using the full vectorial-beam propagation method (FV-BPM) combined with Matlab codes.

2. The 1 × 4 demultiplexer structure and theoretical aspect

Fig. 1(a) shows the x–y cross-sectional view at z = 0 where the orange areas represent GaN and the green and white areas repre-

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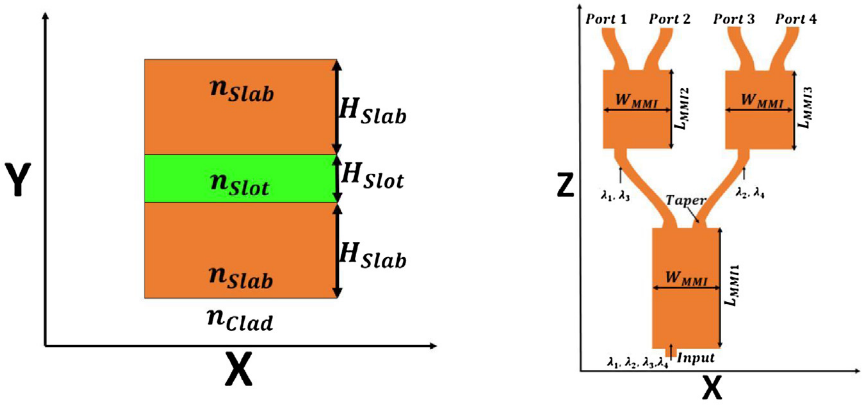

(a) (b)

Fig. 1. An illustration of the 1 × 4 wavelength demultiplexer in the (a) x–y plane and (b) x-z plane.

Table 1
GaN and SiO_2 materials' refractive indices at the operating wavelengths.

λ (nm)	547	559	566	584
$n_{slot} = n_{clad}$	1.4792	1.4787	1.4784	1.4777
n_{slab}	2.416	2.4105	2.4075	2.4004

sent SiO_2. H_{slot} is the height of the SiO_2 layer (slot area), and H_{slab} is the height of the GaN layer (slab area). n_{slot}, n_{slab}, and n_{clad} are the refractive indices of the slot, slab, and cladding, respectively. Table 1 shows the refractive indices of n_{slot}, n_{slab}, and n_{clad} at the operating wavelengths.

Fig. 1(b) shows the x–z cross-sectional view at y = 0, where the three MMI couplers designed for the device are presented. The lengths of the MMI couplers are L_{MMI1}, L_{MMI2}, and L_{MMI3}, respectively, and their width is W_{MMI}.

The width of the input waveguide segment was chosen to be 0.3 μm with a height of 20 μm. The width of the tapers varied from 0.34 μm to 0.3 μm (input/output) with a height of 5 μm. The width of S-bands was chosen to be 0.3 μm to match the width of the output taper, with a height of 40 μm, and the distance between each one of them was chosen to be 0.1 μm.

The MMI is based on the self-imaging effect, which means that every wavelength that enters the coupler will have a direct image of itself periodically. The distance from the point of entry to the point of the first image is called the beat length, and it is given as follows [20]:

$$L_\pi^{\lambda_n} \approx \frac{4 n_{eff} W_e^2}{3\lambda_n}; n = 1, 2, 3, 4. \tag{1}$$

where n_{eff} is the effective refractive index of the fundamental mode in the core area, which includes the slot and slab areas. The FV-BPM mode solver calculates this parameter. λ_n are the wavelengths at which the device is operated, and W_e is the effective width of the MMI couplers. W_e in the case of transverse electric (TE) mode is given by [20]

$$W_e = W_m + \frac{\lambda_n}{\pi}\left(n_{eff}^2 - n_{clad}^2\right)^{-1/2} \tag{2}$$

where W_m is the width of the MMI coupler as shown in Fig. 1b.

To divide two different wavelengths using the MMI coupler, the following conditions must be met:

$$\begin{aligned} L_{MMI2} &= p_1 L_\pi^{\lambda_1} = (p_l + q_1) L_\pi^{\lambda_3} \\ L_{MMI3} &= p_2 L_\pi^{\lambda_2} = (p_2 + q_2) L_\pi^{\lambda} \end{aligned} \tag{3}$$

where p is the integer, L_π is the beat length, and q is an odd number.

To divide four different wavelengths into two outputs using the MMI coupler, the following condition must be met:

$$L_{MMI1} = P_3 L_\pi^{\lambda_1} = (p_3 + q_3) L_\pi^{\lambda_2} = (p_3 + q_3 + 1) L_\pi^{\lambda_3} = (p_3 + q_3 + 2) L_\pi^{\lambda_4} \tag{4}$$

To cancel the third mode from inside the MMI coupler, the input taper was shifted ±(1/6)W_e from the center of the MMI coupler. In addition, the lengths of the MMI couplers were optimized to obtain better performances.

The insertion loss of the device is given as follows:

$$Loss(dB) = -10\ log\left(\frac{P_{out}}{P_{in}}\right) \tag{5}$$

where Pout is the output power and Pin is the input power.

The crosstalk of the device is given as follows:

$$CT_n = \frac{1}{3}\sum_{m=1}^{4} 10\ log\left(\frac{P_m}{P_n}\right) \tag{6}$$

where P_n is the power in the desirable port and P_m is the interfering power in the other port.

3. Results

The Rsoft photonic CAD suite was used to simulate the device, and the device parameters were optimized by FV-BPM simulations combined with Matlab codes. From these calculations, the optimal dimensions of the slot-waveguide were found to be as follows: H_{slot} = 30 nm, H_{slab} = 120 nm, and WMMI = 1.2 μm.

Fig. 2 shows the optimal size of the slot layer and the tolerance values (28.05–31.64 nm) around H_{slot} at 70–100% of the normalized intensity.

Fig. 3(a) and (b) show the electric field patterns of the quasi-TE fundamental mode and minor mode in the x–y plane for a wavelength of 559 nm. A strong confinement of light (red color) can be noticed in Fig. 3(a). The same profile field mode is obtained for the other operating wavelengths.

The effective refractive indices (n_{eff}) were found by solving the major field mode for the operating wavelengths. Fig. 4(a) shows n_{eff} as a function of the operating wavelengths.

By using n_{eff} and W_{MMI} values, Eqs. (1) and (2) can be solved, and the effective width of the MMI coupler (W_e) and the beat lengths of the operating wavelengths can be found. Fig. 4(b) presents the beat lengths as a function of the wavelength.

Combining the solutions of Eqs. (3) and (4), as presented in Fig. 5, with the optimization using the FV-BPM solver, the suitable lengths of each MMI coupler were found to be as follows: L_{MMI1} = 453.2 μm, L_{MMI2} = 157.5 μm, and L_{MMI3} = 158.1 μm. The two