Monolithically Integrating a 180° Bent Waveguide into a III-Nitride Optoelectronic On-Chip System

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Abstract: GaN-based devices have developed significantly in recent years due to their promising applications and research potential. A major goal is to monolithically integrate various GaN-based components onto a single chip to create future optoelectronic systems with low power consumption. This miniaturized integration not only enhances multifunctional performance but also reduces material, processing, and packaging costs. In this study, we present an optoelectronic on-chip system fabricated using a top-down approach on a III-nitride-on-silicon wafer. The system includes a near-ultraviolet light source, a monitor, a 180° bent waveguide, an electro-absorption modulator, and a receiver, all integrated without the need for regrowth or post-growth doping. 35 Mbit/s optical data communication is demonstrated through light propagation within the system, confirming its potential for compact GaN-based optoelectronic solutions.

Keywords: optoelectronic integration; bent waveguide; on-chip system; III-nitride-on-Si

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1 Introduction

The integration of photonic devices on a single chip is a critical advancement in the field of semiconductor optoelectronics, particularly for the development of monolithic systems that combine various functionalities[1 – 5]. One of the primary challenges in advancing silicon photonics lies in the absence of monolithically integrated light sources. This limitation becomes especially pronounced in the ultraviolet and visible spectra, where III-nitride semiconductors offer significant advantages due to their superior optoelectronic properties. Compared with other materials, III-nitride semiconductors are more suitable for integration in these wavelength ranges. Importantly, the process of integrating on-chip light sources using III-nitrides is relatively simple, making them an ideal candidate for optoelectronic applications. The multi-quantum well (MQW) light-emitting diode (LED) serves as a particularly promising device for such integration efforts. Its emission and absorption spectra demonstrate a considerable degree of overlap, which allows for the simultaneous integration of both optical transmitters and detectors at the wafer level[6 – 8]. This overlap has been exploited in various applications, like visible light communication (VLC)[9 – 12], where the rapid modulation of LED intensity facilitates high-speed data transmission.

Recent advancement has demonstrated the potential for a top-down approach to integrating various optoelectronic devices on a single III-nitride chip without requiring complex post-doping or post-growth processes. This method has been used to create microsystems that include both active and passive components[13 – 15]. For instance, experiments have shown that MQW diodes can serve as both the transmitter and receiver in a primitive optical communication system, where one device operates in emission modes and the other in detection modes. The integration of these devices on a single chip has been made possible through the use of integrated waveguides (WG), which facilitates optical interconnection[6, 8]. Furthermore, the monolithic integration of transmitters, modulators, waveguides, and receivers has been successfully achieved, with all components sharing an identical MQW structure[16].

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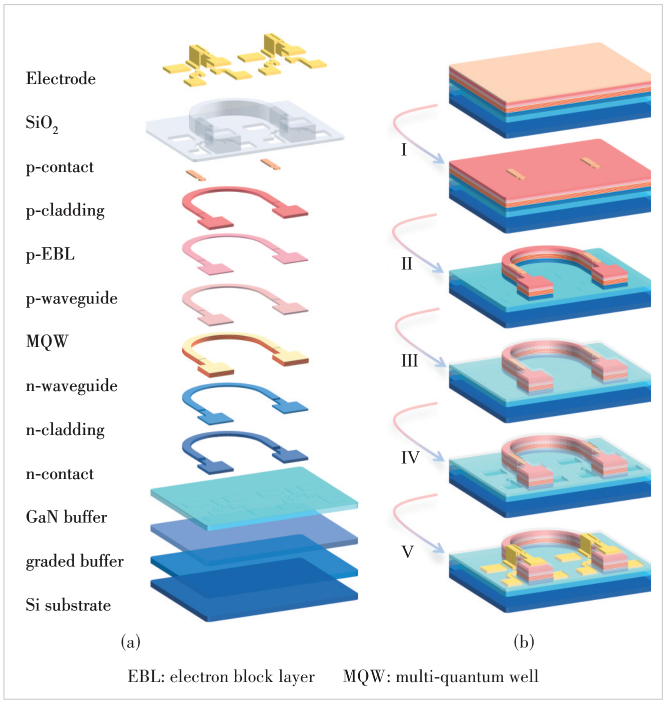
To date, the scalable development of optical interconnection has been faced with the problem of effectively guiding light in extremely narrow bends. However, most existing research focuses on on-chip systems with straight waveguides[13–16], and how to integrate large-angle bent waveguides in these systems remains a key challenge that needs to be explored in depth, especially on III-V and silicon nitride platforms. Solving this problem will be a key factor in promoting the continued progress of optoelectronic integrated systems.

In this paper, we study a monolithic III-nitride optoelectronic microsystem that integrates a near-ultraviolet light source, a monitor, a 180° bent waveguide, an electro-absorption modulator (EAM), and a receiver. The aforementioned components are integrated with an as-grown III-nitride-on-Si wafer uniformly, employing a top-down approach. Detailed characterizations are presented and on-chip optical data communication is demonstrated.

2 Fabrication

The layered structure of the chip and diagram of the fabrication process are shown in Fig. 1. As shown in Fig. 1a, the Si substrate is at the bottom layer. The epitaxial structure is composed of a buffer layer with graded aluminum components, a 2.1 μm-thick unintentionally doped GaN buffer layer, a 2.45 μm-thick Si-doped $Al_{0.03}Ga_{0.97}N$ n-contact layer, a 750 nm-thick $Al_{0.1}Ga_{0.9}N$ n-cladding layer, an 80 nm-thick GaN n-waveguide, the 4-cycle 3 nm/10 nm thick $In_{0.02}Ga_{0.98}N$ / $Al_{0.08}Ga_{0.92}N$ MQWs, a 7 nm-thick $Al_{0.08}Ga_{0.92}N$ last quantum barrier, a 60 nm-thick GaN p-waveguide, a 20 nm-thick $Al_{0.25}Ga_{0.75}N$ electron block layer (EBL), a 500 nm-thick $Al_{0.1}Ga_{0.9}N$ p-cladding layer, and a 30 nm-thick Mg-doped GaN p-contact layer from bottom to top. As shown in Fig. 1b, the active pattern was transferred to a photoresist using a standard photolithography process. The wafer was then etched for 200 nm precisely using an inductive coupling plasma to remove the excess p-contact. The p-mesa of 2.2 μm height was etched out and the n-contact layer was exposed. Two trenches were formed at the same time. A 200 nm-thick SiO_2 passivation layer was deposited on the chip by plasma-enhanced chemical vapor deposition and patterned to realize electrical isolation. 20 nm/200 nm-thick Ni/Au electrode films were deposited by electron beam evaporation and the metal electrode was patterned by lift-off technology. A rapid thermal annealing process was then used to improve the ohmic contact performance in a pure nitrogen environment at 550 °C for 60 s.



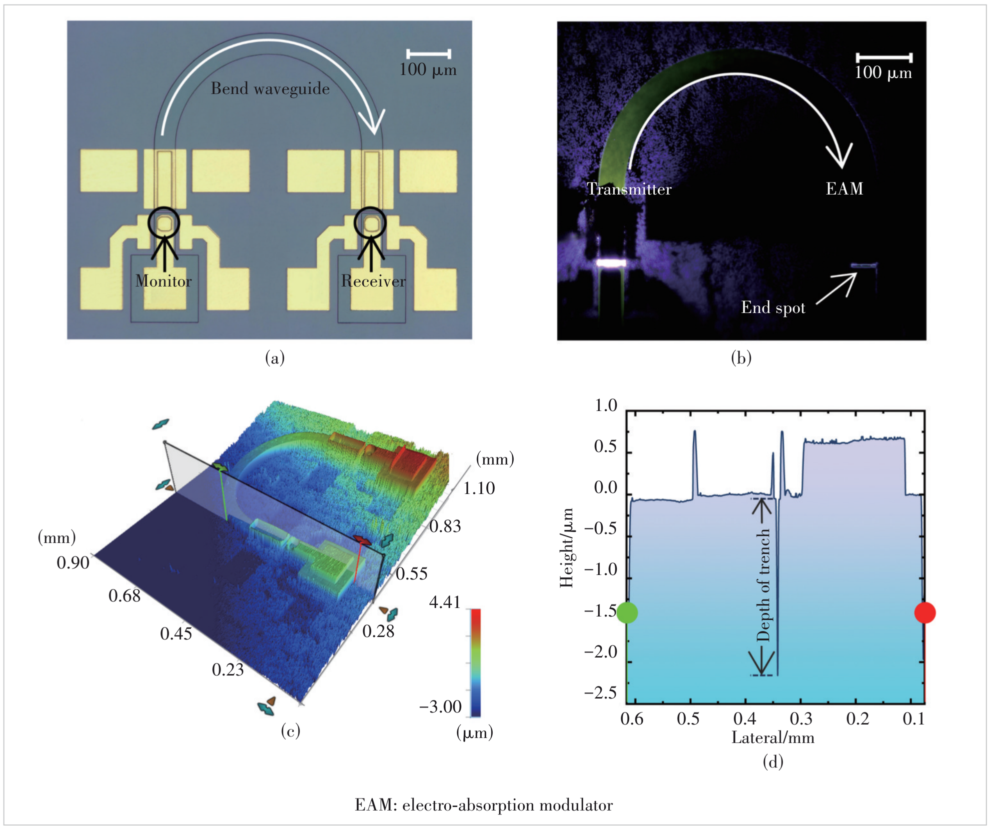
▲ **Figure 1. (a) Layered structure of the III-nitride-on-Si optoelectronic system integrated with a 180° bent waveguide; (b) diagram of the top-down manufacturing process**

3 Results and Discussions

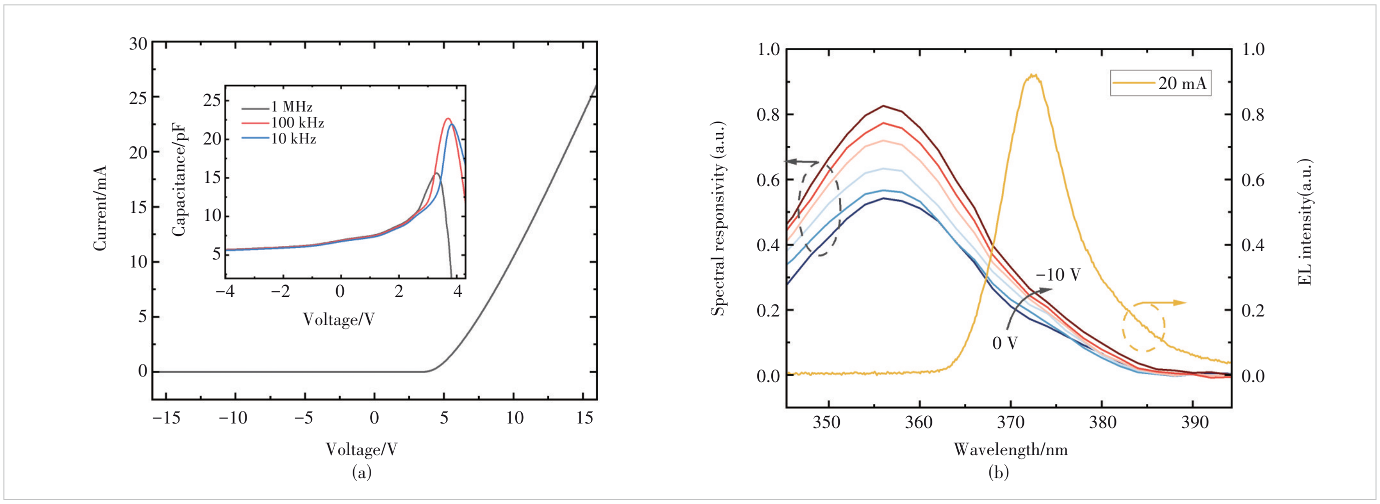
Fig. 2 illustrates the morphological characteristics of the optoelectronic chip. The fabricated chip consists of a monitor, an EAM, a waveguide, a modulator, and a receiver, as shown in the top-view optical microscope image in Fig. 2a. Fig. 2b displays the light spot at the end of the 180° bent waveguide when the transmitter is activated in a dark environment, with the light propagating along the waveguide. The bent waveguide has a width of 50 μm, and the arc length at the center of the waveguide is approximately 740 μm. Fig. 2c presents a 3D surface scan of the chip height, obtained using a high-precision profilometer (DektakXT, Bruker Corporation). The cross-sectional data are shown in Fig. 2d. Electrical isolation between the two devices on the same side is achieved through isolation trenches with a width of 5 μm and an etching depth of 2.2 μm.

Fig. 3 presents the electro-optical characteristics of the active region of the photonic device. The current-voltage (I-V) curve of the transmitter is shown in Fig. 3a, with an inset displaying the voltage-capacitance (V-C) curve of the EAM. The results indicate that the transmitter exhibits typical diode behavior, with a turn-on voltage of around 4 V. When a forward voltage is applied, the capacitance of the EAM initially increases and then decreases to a negative value. This decrease is caused by the radiative recombination of injected carriers within the quantum wells. The electroluminescence (EL) spectrum and spectral responsivity (SR) curve of the photonic chip are shown in Fig. 3b. The spectral analysis is conducted using a high-resolution spectrometer (HR4000, Ocean Insight Corporation) and a quantum efficiency measurement system (Oriel IQE200B, Newport Corporation). The interaction between the Stokes shift and the quantum-confined Stark effect (QCSE) in the photonic chip is reflected in the EL and SR curves. It is well-known that MQW diodes exhibit a distinct Stokes shift between emission (low energy) and absorption (high energy). It is generally accepted that the EL emission originates from the recombination of localized excitons, while the absorption edge of the spectrum corresponds to the absorption of free excitons[17]. When the transmitter's injection current is fixed at 20 mA and the EAM's bias voltage is increased from 0 V to −10 V in steps of −2 V, the overall spectral responsivity shows an increasing trend. The overlap between the EL spectrum and the SR curve enables the MQW diode not only to detect light emitted by another diode with the same structure but also to modulate the light intensity under different reverse bias voltages. As a result, two on-chip MQW diodes with identical structures can serve as the light source and EAM, respectively.

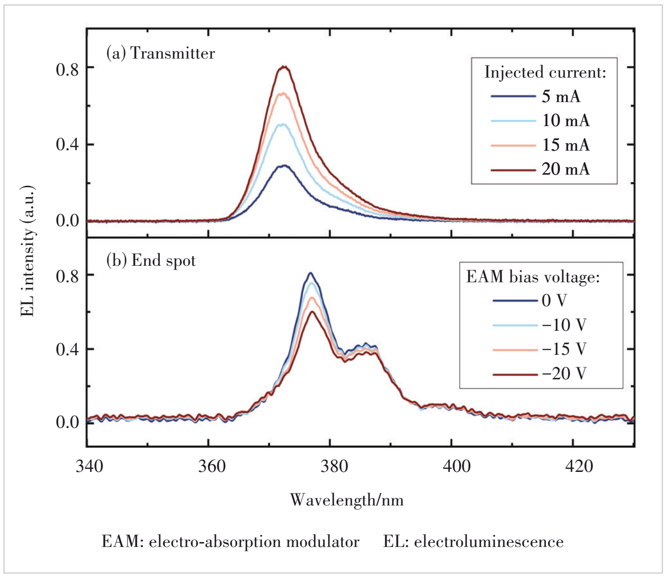
To optically prove that the light from the transmitter can still effectively reach the receiver after propagating through the 180° bent waveguide and generate a light spot on its end face, the spectra of the light spots at both ends of the waveguide are measured, as shown in Fig. 4. The spectra measured at the transmitter/monitor trench are shown in Fig. 4a when the transmitter is stably injected with currents of 5 mA, 10 mA, 15 mA, and 20 mA. The spectra measured at the EAM/receiver trench are shown in Fig.4b while the transmitter is injected with a fixed current of 10 mA, and the EAM is biased with different voltages. The applied bias voltage causes the quantum well band to tilt, and in conjunction with the quantum-limited Stark effect, the EAM can modulate light. A comparison of Figs. 4a and 4b reveals when light propagates through a transmission me-



▲**Figure 2. (a) Birdview of the on-chip system under an optical microscope; (b) luminescence image of the optoelectronic chip; (c) characterization of the mesa height using a stylus profilometer; (d) height characterization along the cross-section in (c)**



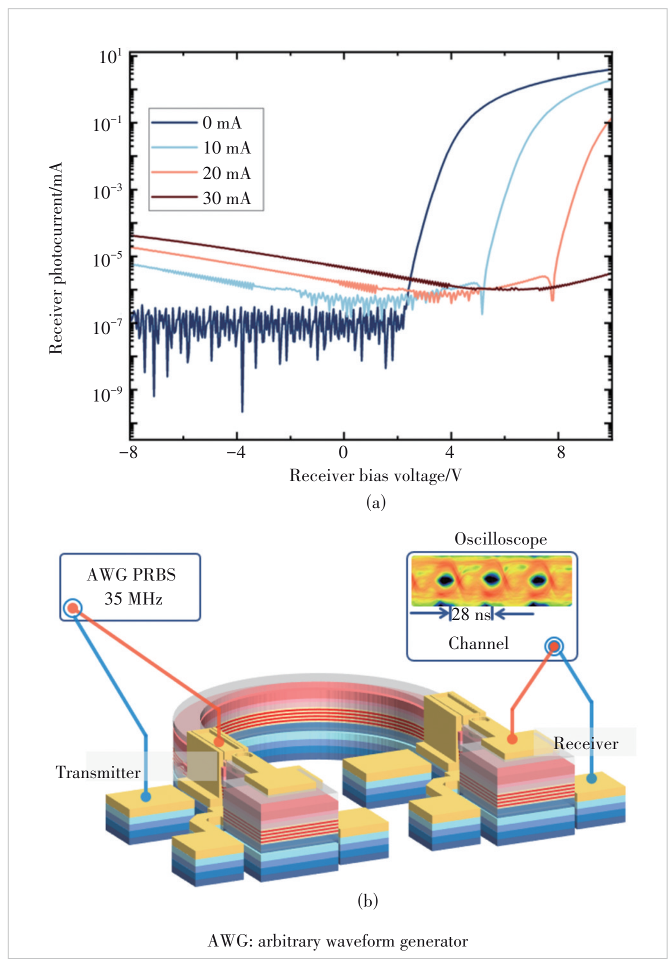
▲**Figure 3. (a) I-V curve of the transmitter, where the inset is the capacitance-voltage curve of the EAM; (b) electroluminescence spectrum and spectral responsivity curves of optoelectronic chip**



▲Figure 4. (a) Electroluminescence spectra of the LED with several different injection currents; (b) spectra of the end spot when the EAM is under different modulation voltages

dium with a quantum well structure sandwiched in the waveguide, the spectrum will be redshifted due to asymmetric absorption[15]. It should be noted that no isolated system is unaffected by the gravitational field, which creates irreversibility. Theoretically, even if a perfect light-emitting device exists, it will absorb higher photon energy than it emits because gravitational fields would cause the irreversibility between the photon emission and absorption process[18 – 19]. The object at different positions has different quantized states in a gravitation field and thus, its mass related to its total internal energy is different at different energy states, because the total internal energy equals its mass times the speed of light squared, $E = mc^2$. According to the law of conservation of energy, the total energy of the system is conserved. Therefore, the work done during the process from one position to another position is not symmetric to that done during the return trip, which creates irreversibility. The frequency difference can be expressed as $\omega_{det} - \omega_{emi} = \left(E_{gap} gH\right) / hc^2$, where ω_{det} is the frequency of the detected light, ω_{emi} is the frequency of the emitted light, E_{gap} is the energy gap between the conduction and valence bands in a gravitational field, h is the Planck constant, c is the velocity of light, g is the normalized acceleration, and H is related to the geometrical height between the conduction and valence bands in a gravitational field. The frequency difference is tiny because the physical height H of the energy gap is small. However, both EL spectra and responsivity spectra are broad. Moreover, the shift in the EL versus responsivity spectra in reality is also caused by either the loss of energy in the excited state to lattice modes or changes in molecular configuration and vibrational modes. Therefore, there is an asymmetric overlap between the emission and the detection spectra. The experimental results indicate that the asymmetric absorption would cause spectral redshift in a quantum well diode, and self-absorption is a fundamental phenomenon in quantum wells. This suggests that the next monolithic GaN optoelectronic integration could be improved through some spectral fine-tuning techniques, such as selective area growth[20] and transfer processes[21].

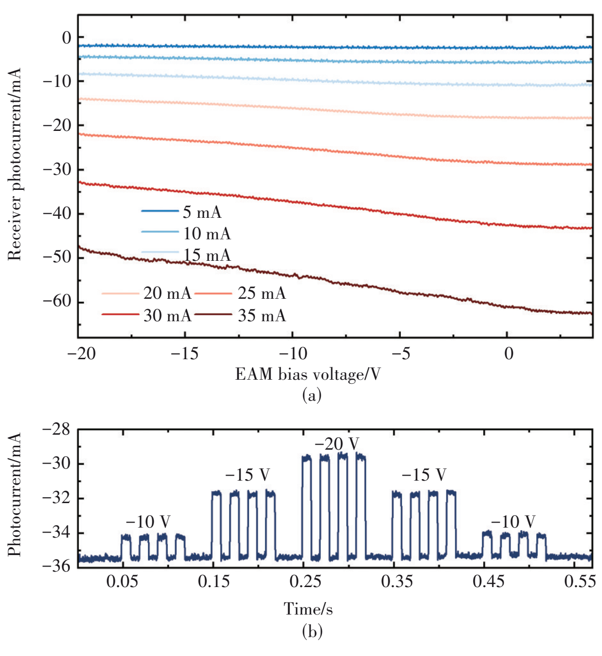
The characterization and testing of optical transmission and reception between two on-chip diodes with identical structures are shown in Fig. 5. As mentioned earlier, quantum well diodes can absorb photons emitted by another diode of the same structure and generate a corresponding photocurrent. To evaluate the optical response between the quantum well diodes at both ends of the curved waveguide, the two diodes are used as a light-emitting transmitter and receiver, respectively, as illustrated in Fig. 5b. When the injection current of the transmitter increases from 0 to 30 mA, the photocurrent of the receiver varies with the applied voltage, as shown in Fig. 5a. A higher injection current in the transmitter results in stronger emitted light, producing more photons. Consequently, under the same



▲Figure 5. (a) Receiver photocurrent versus applied voltage at different transmitter injection currents; (b) 35 Mbit/s on-chip data transmission test with emission modulation mode

applied voltage, a larger injection current in the transmitter leads to a greater photocurrent in the receiver. It is evident that the larger the reverse bias voltage applied, the greater the photocurrent generated by the diode. This trend is consistent with the SR curve plotted in Fig. 3b. Fig. 5b demonstrates the 35 Mbit/s on-chip small-signal data transmission between the transmitter using emission modulation and the receiver. The transmitter is driven by a pseudo-random binary sequences-11 (PRBS11) signal from an arbitrary waveform generator (AWG) with a 2-peak-to-peak voltage (Vpp) amplitude, 7 V bias voltage, Hi-Z output impedance, default phase, and a frequency of 35 MHz. These parameters are synchronized with another channel to trigger the oscilloscope. After a few seconds, a clear eye diagram appears on the oscilloscope, as shown in Fig. 5(b). This confirms that the photonic chip with a 180° bent waveguide is capable of on-chip optical signal transmission using emission modulation.

After the characterization of the emission modulation mode of the transmitter, the absorption modulation mode of the quantum well diode as an EAM was characterized, as shown in Fig. 6. Four channels of the Keysight B1500A semiconductor parameter analyzer were connected to the transmitter, EAM, and receiver. The transmitter was provided with a constant DC drive, the EAM was supplied with a reverse bias voltage in a sweep mode, and the I-V characteristics of the receiver were measured. The drive current was sequentially set to 5 mA, 10 mA, 15 mA, 20 mA, 25 mA, 30 mA, and 35 mA.



▲Figure 6. (a) Photocurrent change of the receiver as the voltage biased on the modulator varies with the transmitter under different operating currents; (b) waveforms of the receiver's photocurrent when EAM is modulated

For each transmitter current condition, the I-V characteristics of the receiver were measured as the EAM bias voltage was swept from 4 V to −20 V. Fig. 6a shows the relationship between the photocurrent of the receiver and the reverse bias voltage applied to the modulator. The change in absorption is attributed to the QCSE induced by the external field[22–23]. At the same modulation voltage, as the injection current increases, the transmitter's light intensity also increases, leading to more pronounced changes in the amplitude of the photocurrent. Fig. 6b displays the photocurrent waveform during on-chip optical data transmission using the absorption modulation mode. The transmitter was driven by a constant 20 mA current, and the EAM switched between zero and different reverse bias voltages to modulate the absorption of the light transmitted through the waveguide. This reduced the light reaching the receiver, causing corresponding changes in the photocurrent output from the receiver thereby achieving on-chip electro-absorption modulation in the photonic chip. When the reverse bias voltage of the EAM is 20 V, the total power consumption of the system on chip is about 250 mW.

4 Conclusions

In summary, a monolithic optoelectronic on-chip system integrated with 180° bent waveguide was fabricated from a III-nitride-on-Si wafer. The experimental results demonstrate that the light transmitted through the curved waveguide can be extracted by the receiver at the end of the waveguide, and that the absorption modulation signal on the propagation path can be detected. The monolithic integration method adopted in this paper simplifies the fabrication process, avoiding complex post-doping and growth steps, while achieving a highly integrated design of the transmitter, modulator, waveguide, and receiver. Through the shared MQW structure, the system demonstrates excellent scalability, particularly with the successful integration of large-angle bent waveguides. This provides strong support for realizing bidirectional optical signal modulation in III-nitride optoelectronic systems, laying the foundation for further development of monolithic optoelectronic systems in the future.

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