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PLC-type variable optical attenuator operated at low electrical power

Y.O. Noh, M.-S. Yang, Y.H. Won and W.-Y. Hwang

A novel voltage-controlled variable optical attenuator based on a polymeric planar lightwave circuit (PLC) is demonstrated. The fabricated variable attenuator shows 30dB attenuation with only 80mW electrical input power at 1.55μm. The polarisation dependences at 0 and 10dB attenuations are 0.2 and 1dB, respectively. The rise and fall times are less than 5ms.

Introduction: Optical power fluctuation is detrimental to the overall performance of an optical transmission line and can be compensated by use of variable optical attenuators (VOAs). Such compensation is particularly required at linear repeaters and channel power equalisers in wavelength division multiplexed (WDM) networks [1]. VOAs have been fabricated by several technologies such as optomechanical systems, microelectromechanical systems (MEMS) [2], side-polished fibre devices, and Faraday rotators. New VOAs integrated on a PLC have recently been reported, with structures comprising a Mach-Zehnder interferometer [3] or asymmetric Y-branch waveguide [1]. VOAs on PLC are usually fabricated using polymer or silica on silicon substrates [4]. Polymeric VOAs are particularly attractive due to their low electrical power consumption, low cost and easy fabrication. In this Letter, we propose a novel polymeric thermo-optic (TO) VOA structure with superior characteristics than previous structures.

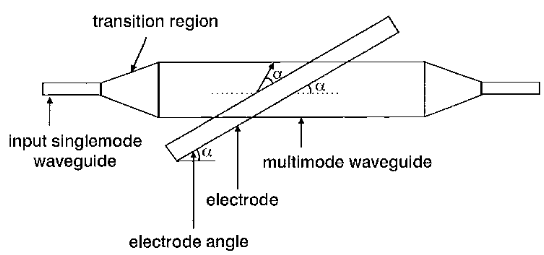

Fig. 1 *Schematic diagram of proposed variable optical attenuator*

Principle of operation: Fig. 1 shows a schematic diagram of the proposed VOA. It consists of input and output singlemode waveguides, tapering regions, a multimode waveguide, region and angled electrode with α. The basic operation principles are as follows. The light is first expanded adiabatically from the singlemode waveguide into the multimode waveguide, which supports at least six waveguide modes. When the voltage is applied along the electrode, the refractive index under the heater is lowered due to the thermo-optic (TO) effect. Therefore, the propagating light under the heater is partially reflected at an angle of 2α with respect to the horizontal axis. If the angle is larger than the fundamental mode of the multimode region, the reflected light is coupled back into the higher order guiding modes after passing the heater. These higher order modes are successively filtered out through the output tapering region and the output singlemode waveguide. As the applied voltage increases, the amount of the reflected light increases, which leads to a larger attenuation according to the applied voltage.

Device design and experiment: The waveguide was a buried-channel type with 7 × 7μm rectangular cross-section. The core and clad materials were ZP1010™ and ZP2145™, respectively, polymer materials synthesised at ZenPhotonics Co. The polymer materials are thermally cross-linkable at 250°C. The birefringence between the TE and TM modes are ~0.0036 at 1550nm for both the core and the cladding materials, and the refractive index difference between the core and the cladding is 0.7%.

When the light propagates from the singlemode waveguide to the multimode waveguide region, a slight higher order mode excitation is inevitable if the tapering region is not sufficiently long. This higher order mode coupling has the effect of causing multimode interference in the multimode waveguide region, so that the excess loss varies sinuously with the length of multimode waveguide. Therefore the length should be optimised for a given waveguide width and index difference. In this Letter, the length of the waveguide is optimised to 3800μm at a multimode waveguide width of 40μm.

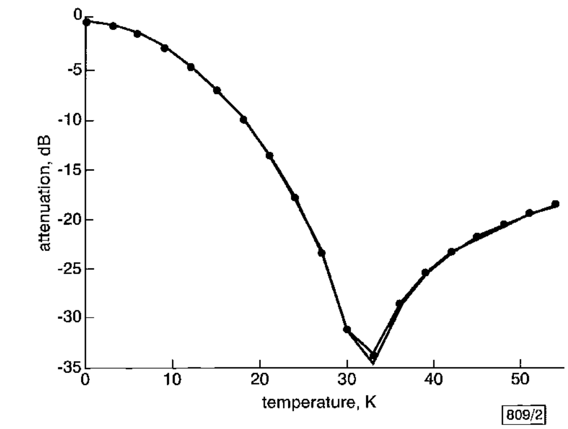

Fig. 2 *Calculated result of attenuation characteristics against temperature*

- - - TE mode
● TM mode

Fig. 2 shows the attenuation characteristics of the attenuator calculated using the beam propagation method (BPM), in which the operating wavelength is 1550nm. The length, the width and the angle of the heater are optimised to give a maximum attenuation for a given temperature change and are selected as 3800μm, 7.2μm, and 1.6°, respectively. The solid line is the attenuation characteristic of the TE mode and the dotted line is that of the TM mode. They show nearly the same attenuation behaviour, with a difference of < 1dB even at 30dB attenuation.

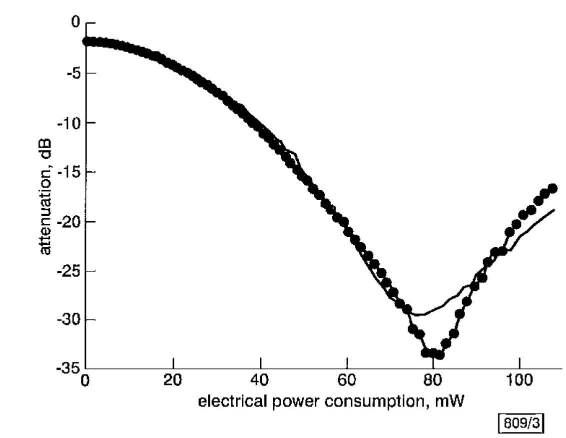

Fig. 3 *Measured attenuation characteristics against applied electrical power*

Electrode length; 3800μm, electrode width; 7.2μm and electrode angle; 1.6°
——— TE mode
● TM mode

Fig. 3 shows the measured results of the fabricated devices. The result shows that the electrical power required to achieve 30dB attenuation is only 80mW. This result, which shows very high attenuation at low electrical power consumption, provides a good combination that can be used in normal transport networks. The polarisation dependence is less than 0.2 and 1dB at 0 and 10dB attenuations, respectively. However, the polarisation dependence is higher than the simulated results. Such deviation may come from a slight difference in the confinement factors of the TE and TM modes in real devices. The rise and fall times are measured to be ~5ms. The insertion loss of the device is < 2dB. The fabricated devices have a very compact size of $2 \times 25\text{mm}^2$, which can be further reduced to $2 \times 15\text{mm}^2$. This device shows superior characteristics compared to previous results in terms of size and power consumption.

Conclusions: A novel and compact VOA based on higher order mode excitation and singlemode filtering mechanisms has been proposed and fabricated on a polymer PLC. The device shows 30dB attenuation with only 80mW input electrical power.

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10Gbit/s high sensitivity, low-voltage-operation avalanche photodiodes with thin InAlAs multiplication layer and waveguide structure

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The development of waveguide avalanche photodiodes with a very thin 0.1 μm multiplication layer for use in high-speed, high-sensitivity, low-voltage-operation receivers is presented. A η = 76%, a GB product of 180GHz, and a breakdown voltage *Vb* of 15V were obtained. The 10Gbit/s bit error rate measurement showed a sensitivity of –28.8dBm (BER 10^{-9}, PRBS 2^{23}–1), which is the highest sensitivity yet reported for APD receivers.

Introduction: High-speed, high-sensitivity photodiodes are key components for use in compact and low-cost receivers in high-bit-rate optical communication systems. Recently, high-gain-bandwidth-product and low-multiplication-noise avalanche photodiodes (APDs) have been reported with thin multiplication layers made of various materials [1 – 3]. We have demonstrated that 0.05–0.10μm-thick InAlAs layers can be used in separated-absorption and multiplication (SAM) APDs [4]. With a 0.1μm multiplication layer and back-illuminated mesa structure, a high GB product of 140GHz, an operation voltage of 18.8V, and quantum efficiency of 47% have been demonstrated [5].

In this Letter we report a waveguide APD (WG-APD) with a 0.1μm InAlAs multiplication layer. A multimode waveguide structure [6, 7] and a very thin InAlAs multiplication layer enable both a high quantum efficiency and low voltage operation, simultaneously. We measured the bit error rate (BER) at 10Gbit/s to prove the high sensitivity.

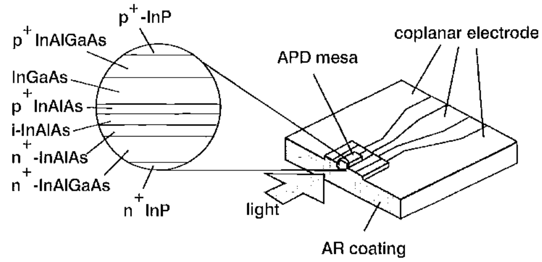

Fig. 1 *Schematic diagram of InAlAs-WG-APD*

Device design: Fig. 1 shows a schematic diagram and the structure of the InAlAs-WG-APD. The waveguide structure consists of upper and lower InAlGaAs guide layers and InAlAs/InGaAs SAM layers as a core region. Using a beam propagation method, we estimated the quantum efficiency to be 78% for 0.7μm-thick InAlGaAs (λ_g = 1.3μm) guide layers and a 0.5μm-thick InGaAs absorption layer, when the waveguide was 30μm long. This efficiency is high enough for a high-sensitivity APD receiver.

In general, reducing the multiplication layer thickness increases the GB product owing to the short avalanche build-up time. In contrast, a high electric field increases the tunnelling dark current. The measured dark current density increased rapidly when the InAlAs multiplication layer thickness was < 0.1μm [4]. Based on this experiment, we determined that the minimum multiplication layer thickness should be 0.1μm, so as not to deteriorate the receiver sensitivity.

The APD structure was grown by gas source molecular beam epitaxy on a semi-insulating InP substrate. The thicknesses of the multiplication, field buffer, and absorption layers were 0.10, 0.02, and 0.50μm, respectively. The 6μm-wide waveguide mesa was fabricated by wet chemical etching. The APD mesa was then passivated with SiNx. The electrodes formed a coplanar transmission line to match the impedance of 50Ω.

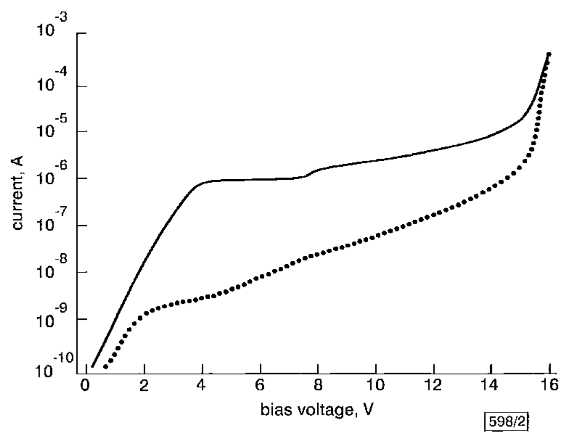

Fig. 2 *Current-voltage characteristics of InAlAs-WG-APD*
— photocurrent
– – – – dark current

Experimental results and discussions: Fig. 2 shows *I-V* characteristics under dark and illuminated conditions for a 30μm-long device. The breakdown voltage *Vb* was 14.8V, which is the lowest value yet reported for a 10Gbit/s APD. The multiplied dark current I_{dm} was 40nA at a multiplication factor *M* of 10, which gives a negligible power penalty of < 0.5dB in a 10Gbit/s system. The external quantum efficiency η at a 1.54μm wavelength was 76%, using a hemispherically ended fibre. The measured device capacitance, including parasitic capacitance, was 0.1pF. The 3dB-down bandwidth *FC* against the multiplication factor *M* is shown in Fig. 3. A maximum *FC* of 32GHz with 25Ω load and a GB product of 180GHz were obtained. The wide bandwidth of the InAlAs-WG-APD is also suitable for receivers over 10Gbit/s.

The 10Gbit/s back-to-back sensitivity was measured, using a 40μm waveguide length device and a preamplifier IC [8]. Hemi-