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Wavelength Monitoring With Low-Contrast Multimode Interference Waveguide

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Abstract—We demonstrate a wavelength monitor based on interference effect in planar quantum-well waveguide fabricated using argon plasma quantum-well intermixing. The passive device exhibits a characteristic curve, which is used to determine the wavelength of an arbitrary input light near the 1550-nm window. It has an exponential-like wavelength response in the wavelength range 1520–1620 nm and resolution of 0.2 nm.

Index Terms—Integrated optics, multimode waveguides, quantum wells, wavelength measurement.

I. INTRODUCTION

A WAVELENGTH monitor is an important component for wavelength-division-multiplexed communication systems, especially with wavelength-tunable lasers replacing the fixed-wavelength sources such as conventional distributed feedback lasers. For current optical communication systems, tunable semiconductor lasers need to vary the wavelength over up to 40 nm, and in 0.4- and 0.8-nm spacing [1]. To maintain the wavelength stability over the tuning range, integrated wide-band wavelength monitors are needed, in the same way as integrated photodiodes were used to maintain the power stability of single-frequency lasers.

Existing wavelength monitoring techniques are based on arrayed waveguide grating [2] and in-line photodetectors [3]. While these devices can be integrated monolithically with semiconductor lasers, they have drawbacks such as their large sizes and the requirement of additional bias currents, respectively.

Multimode interference (MMI) waveguides are commonly used as a splitter-combiner in photonic integrated circuits due to their large bandwidth, low polarization sensitivity, and good fabrication tolerance [4]. It was demonstrated that by asymmetric excitation of waveguide modes, the power splitting ratio has wavelength-dependent characteristics [5]. The additional advantage of using MMI waveguides is the compatibility of fabrication processes with other photonic devices [6]. We have proposed a modification to this design in [7], where an MMI waveguide supporting more than two lateral modes was studied. This helps separate the output waveguide and ease the fabrication, while also increasing the output contrast. In this letter, we report an experimental realization of this new design. To demonstrate the possible integration with semiconductor light sources, the wavelength monitor has been fabricated using a laser structure, which has undergone an intermixing

process using argon plasma [8]. The fabricated device provides an unambiguous wavelength signature over a 100-nm range, which covers the whole *C*- and *L*-band of telecommunication wavelength.

II. DEVICE STRUCTURE AND PRINCIPLE OF OPERATION

The operation of an MMI waveguide is best described in terms of the principle of self-imaging [9]. An input field excites the supported modes of the waveguide. These modes propagate at different phase velocities, and beating occurs at periodic intervals along the propagation direction. The beating results in the formation of self-images of the input field. The position of these images can be expressed in terms of the coupling length L_C , which is given as

$$L_C = \frac{4n_r W_{\text{eff}}^2}{3\lambda} \quad (1)$$

where the effective waveguide width

$$W_{\text{eff}} = W + \frac{\lambda}{\pi} (n_r^2 - n_c^2)^{-\frac{1}{2}} \quad (2)$$

where n_r and n_c are waveguide and cladding refractive indexes, and λ is the free-space wavelength.

The proposed wavelength monitor consists of a central MMI waveguide, two output waveguides, and one input waveguide positioned at $2/3$ of the width of the MMI waveguide as shown in Fig. 1(a). $W/3$ and $2W/3$ coincide with the zeroes of mode 2, 5, 8, ... of the MMI waveguide and a Gaussian input field will not excite these modes. By this selective excitation, the position of the first self-image can be reduced from $3L_C$ to L_C [9].

There is a wavelength dependency in beat length $L_C(\lambda)$, and thus, the positions of self-images. We designed the MMI-based wavelength monitor by making the MMI length equal to $L_C(\lambda_0)$ for a nominal wavelength λ_0 . With λ_0 input, the optical power is transferred efficiently into the cross output waveguide. However, as the input wavelength deviates from λ_0 , the optical power will leak into the bar output waveguide [see Fig. 1(b)]. We have shown that this phenomena can be exploited for efficient monitoring of the input wavelength [7]. Using the ratio of output power in the cross and bar waveguides, the input wavelength can be identified independently of the input power.

The accuracy of this method relies on measuring the output powers with the same efficiencies. This can be best achieved by fabricating identical photodetectors at the termination of each output waveguide. In this study, we did not attempt the photodetector integration. To ensure the measurement responses were the same, a single external photodetector is used to measure both

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Fig. 1. (a) Structure of the MMI waveguide wavelength monitor. (b) Beam-propagation method simulation of the device. (c) Scanning electron micrograph of the fabricated wavelength monitor on InP substrate.

the output powers, with a single set of coupling optics. The coupling efficiency was maximized before the measurement of each output power.

III. FABRICATION AND EXPERIMENTAL RESULTS

The MMI wavelength monitor was fabricated using a lattice-matched InGaAs–InGaAsP quantum-well structure grown by metal–organic vapor phase epitaxy on InP substrate [8]. The room temperature emission wavelength is 1550 nm. The waveguiding layers consisted of a multiple (five) quantum-well region and two levels of graded index (GRIN) InGaAsP layers. To provide transparency at the laser emission wavelength, the bandgap energy has to be modified before the waveguides are fabricated. By spatial-selectively modifying the bandgap energy, the device can potentially be integrated with a laser source on the same substrate. The quantum wells and barriers were interdiffused by means of argon plasma-induced quantum-well intermixing (QWI). The plasma was generated in an inductively coupled plasma (ICP) system (Oxford Instrument System 100). The argon plasma exposure introduced point defects into the material surface, and these point defects were driven through the quantum-well regions during the rapid thermal processing and promote material mixing between wells and barriers. Photoluminescence (PL) measurement of the sample were made at 77 K before and after intermixing, and the results are shown Fig. 2. The intermixing introduced 92-nm shift of the PL peak, which is adequate to make the structure transparent to the light near

Fig. 2. 77-K PL spectra of sample before and after QWI.

1.55- μm wavelength at room temperature. A measured waveguide loss of 2.98 cm^{-1} was demonstrated using an external cavity laser with the above technique [8].

We fabricated the MMI waveguide and the S-bends by a multiple plasma etch process. First the structure was pre-etched to leave 200 nm of p-InP cladding on top of the GRIN layers. Then the waveguide patterns were transferred to the SiO_2 mask layers by reactive ion etching, and the waveguides were etched with a $\text{CH}_4\text{--H}_2$ ICP plasma process. The S-bend region was subjected to an additional plasma etch, which completely removed the quantum well and GRIN layers in the side portions of the S-bends. This reduced the effective index of the side portion to unity and provided a high contrast waveguide that confined light more tightly and allowed small radius S-bends to be fabricated [Fig. 1(c)]. On the other hand, the MMI region is a low contrast waveguide with typical refractive index difference of 1%. This allows better control of the number of supported waveguide modes, which plays an important role in the range and sensitivity of the MMI waveguide monitor [7].

To characterize the wavelength monitor, we measured the power splitting fraction

$$F = \frac{P_{\text{cross}}}{P_{\text{cross}} + P_{\text{bar}}} \quad (3)$$

of the device as the input wavelength was scanned from 1520 to 1620 nm. The transverse electric (TE)-polarized input light from an external tunable laser source was coupled into the device using a tapered-end single-mode optical fiber, which focused light onto the $2.5\text{-}\mu\text{m}$ -wide input waveguide. The two output signals were butt-coupled with a multimode fiber and measured with an unbiased Ge photodetector and a lock-in amplifier. The measured wavelength response is in good agreement with the simulated result using the beam propagation method (BPM), as shown in Fig. 3. The small discrepancy in short wavelength end is due to the fact that the refractive index variation with wavelength has not been taken into account in the BPM simulation. The wavelength range used in this study was restricted only by the external tunable light source. The waveguide geometry used in BPM simulation was taken from the fabricated device, with the MMI waveguide width and length 12.6 and $451\text{ }\mu\text{m}$, respectively. At this width, the waveguide supports the first six propagation modes. The length was chosen to coincide with the first mirror image in the MMI waveguide [10]. A near-field image

Fig. 3. Output power fraction in cross port, as a function of wavelength. The inset shows near-field pattern of the output with asymmetric power splitting into the two outputs.

of the output light from both waveguides was taken with an infrared charged couple device imager and is shown as the inset in Fig. 3.

Fig. 3 shows a monotonic increase of the power fraction in the cross output with increasing input wavelength. With this characteristic, the wavelength of an arbitrary input light coupled into the device can be analyzed by measuring the powers coupled into the output waveguides, since the power fraction has a one-to-one correspondence to the input wavelength within the range observed. Propagation through the 50- μm -long single-mode input waveguide ensures a good beam profile of the input field, and proper excitation of the MMI waveguide modes.

The characteristic curve is exponential-like, and the precision in determining the input wavelength increases toward longer wavelength. The wavelength resolution of this class of wavelength monitor can approximately be expressed as

$$\Delta\lambda = \frac{1}{S/N} \frac{\partial\lambda}{\partial F} \sqrt{1 + 2F^2} \quad (4)$$

where S/N is the signal to noise ratio in the detection system, and $\partial\lambda/\partial F$ is the reciprocal slope of the characteristic curve in Fig. 3. In this study, the dominant parameter in (4) is $\partial\lambda/\partial F$ and the wavelength monitor's precision increases with the slope of the characteristic curve. With 2-mW input and noise equivalent power of 100 nW, the average wavelength resolution of the device is 0.2 nm across the 100-nm wavelength range. The results above were derived for TE-polarized input. While the difference of F for TE and transverse magnetic (TM) polarization can be up to 1%, planar semiconductor lasers typically emit light with very large TE/TM ratio and the polarization effect is insignificant.

The epitaxial structure used allows planar integration with semiconductor laser and quantum-well photodetectors, and thus, further improvement of wavelength precision is possible due to the reduction of noise from ambient lights. To improve the sensitivity still further, it is theoretically possible to use waveguide n times as long, and couple out the higher order image of the input beam. The increased modal dispersion will result in larger $\partial F/\partial\lambda$, at the expense of the wavelength coverage.

IV. CONCLUSION

We have demonstrated a new class of wavelength monitor working at around 1550-nm wavelength window. The device makes use of interference effect in an MMI waveguide to provide dispersion and does not require any electrical bias. We have demonstrated a single device capable of wavelength monitoring across 100-nm range with a resolution of 0.2 nm. The fabrication processes are simple and compatible with other important photonic components. These characteristics highlight the potential of MMI-based wavelength monitor for optical telecommunication applications.

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