Highly Polarized Single-Chip ELED Sources Using Oppositely Strained MQW Emitters and Absorbers

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***Abstract*—Integrated polarizer components with polarization extinctions >40 dB are desirable for state-of-the-art photonic integrated circuits. We demonstrate >60-dB polarization extinction from a single-chip InGaAsP–InP broadband source by combining an edge light-emitting diode consisting of compressively strained quantum wells (QWs) with an absorber consisting of tensile strained QWs. A 600-μm polarizer exhibits only 5 dB of insertion loss.**

***Index Terms*—Edge light-emitting diode (ELED), photonic integrated circuits (PICs), polarization, strained quantum well (QW).**

I. Introduction

PHOTONIC integrated circuits (PICs) with dynamic functionality are attractive alternatives to optical systems based on discrete components. However, the fabrication of complex PICs with extreme polarization control of the optical signal is quite difficult. This is due to the mixed emission and absorption of the transverse-electric (TE) and transverse-magnetic (TM) polarization modes in semiconductor materials such as InGaAsP–InP. Adding strain to these materials can greatly increase or decrease the TE/TM ratio, but this alone provides limited polarization extinction levels. Furthermore, integrated polarizer components have not demonstrated polarization extinctions between TE and TM modes in excess of about 20 dB in InGaAsP–InP [1], [2]. Devices such as fiber-optic gyroscopes demand polarization extinctions of at least 40 dB to achieve only moderate sensitivity levels [3]. Thus, to realize a highly sensitive, single-chip gyroscope, there is a clear need for novel approaches to polarization control.

We previously reported polarization extinctions of 40 dB by optimizing only the light source [4]. Our approach utilized compressively strained high-gain multiple quantum wells (MQW) as the active region in an edge light-emitting diode (ELED). To achieve even greater extinction, we have designed an on-chip polarizer that functions in conjunction with our highly polarized ELEDs to demonstrate a TE polarized device with >60-dB polarization extinction.

II. Device Design

Our polarizer approach uses strained MQW active regions. When strain is induced in the MQW, the degeneracy between the light hole (LH) and heavy hole (HH) bands at $k = 0$ splits. Compressive strain pushes the light hole band to higher energies than the heavy hole band so that conduction band (CB)-HH transitions, which provide gain/absorption to TE polarized light at $k = 0$, dominate. Tensile strain results in the opposite behavior so that CB-LH transitions, which are mostly TM polarized (and to a lesser extent TE polarized), dominate [5]. By combining a compressively strained (TE dominant) source with a tensile strained (TM dominant) MQW absorber that functions as a polarizer, the TM light generated by the ELED will be selectively absorbed, and very high polarization extinctions can be achieved (Fig. 1).

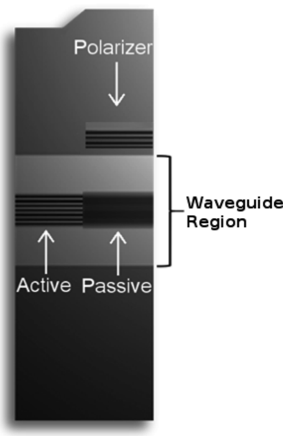

Fig. 1. Side-view schematic of MQWs used for integrated ELED/polarizer device. The active QW region is centered in the waveguide to maximize the confinement factor at 13%, while the polarizer QW region is placed above the waveguide to reduce the confinement factor to 2.3%.

The combined ELED/absorber devices were grown via metal–organic chemical vapor deposition (MOCVD) on a sulfur-doped InP substrate. The ELED MQW region of this device consisted of ten 6.5-nm InGaAsP QWs and eleven 8.0-nm InGaAsP barriers. The QW composition was chosen to create compressive strain (+0.9%) in the wells for TE dominant light output at 1550 nm and the barriers were grown with a small degree of tensile strain (−0.2%) for strain compensation. In the ELED region, the MQW was centered between symmetrical waveguides for a maximized optical confinement (Γ) of $\sim$13%. Active and passive waveguide regions were obtained by selectively shifting the active ELED bandedge from a photoluminescence peak (λ_{PL}) of 1540–1430 nm using quantum-well (QW) intermixing as described in [6].

Two different polarizer designs with the same QW compositions were examined (Table I). The QW width in Design 1

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TABLE I
POLARIZER EPITAXIAL STRUCTURE

	Number of QWs	QW Thickness (Å)	PL Wavelength (nm)
Design 1	2	130	1548
Design 2	3	95	1515

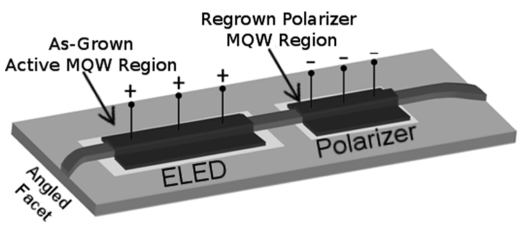

Fig. 2. Schematic of ELED device illustrating the integrated polarizer and angled/flared output facet.

was selected to align the polarizer absorption peak ($\lambda_{\rm PL} = 1548$ nm) with the gain peak of the ELED ($\lambda_{\rm PL} = 1540$ nm) to absorb TM light generated at any wavelength below the ELED $\lambda_{\rm PL}$. But, since CB-LH transitions also permit some TE absorption, a second design was explored with narrower QWs to blue-shift the polarizer absorption peak ($\lambda_{\rm PL} = 1515$ nm) relative to the ELED $\lambda_{\rm PL}$ to reduce undesirable TE absorption.

The polarizer MQW regions were realized via an MOCVD regrowth. An InP spacer layer on top of the waveguide offset the polarizer region MQW from the peak of the optical mode, reducing Γ to only 2.3%. The thickness of this spacer layer was chosen to keep Γ constant between the two designs. The polarizers employed tensile strained InGaAs wells (-1%) and 8.0-nm compressively strained InGaAsP barriers (0.3%). The polarizer region was defined using wet etching techniques. A subsequent regrowth defined the p-type cladding. This high-functionality PIC fabrication approach is described in [6].

The completed 3-μm-wide surface ridge waveguide devices consisted of a 1000-μm ELED, followed by a short passive section, a 300- to 1000-μm integrated polarizer, and a curved/flared output waveguide to reduce reflections (Fig. 2).

III. EXPERIMENTS AND DISCUSSION

Using a Glan Thompson polarizer to resolve the output polarization as in [4], the polarization extinction was measured for devices with and without an on-chip MQW polarizer. Fig. 3(a) shows the TE and TM polarization-resolved amplified spontaneous emissiong (ASE) spectrum from an ELED at 8.3 kA/cm^2 and the total output spectrum with no external polarizer. The TM-dominant CB-LH transition occurs at a higher energy than that of the TE-dominant CB-HH transition, and thus the peak wavelength of the TM spectrum ($\sim$1478 nm) is blue shifted from the peak wavelength of the TE spectrum (1545 nm). The peak at 1545 nm in the TM-resolved spectrum corresponds to TE light that our polarizing prism, which provided only $\sim$27 dB of polarization extinction, could not filter out [4]. When the Glan Thompson polarizer is removed from the system, both peaks are evident in the spectrum. With a TM peak power of -66 dBm and a TE peak power of -22 dBm, the native polarization extinction between the TE and TM peak powers of the 1000-μm ELED is $\sim$44 dB.

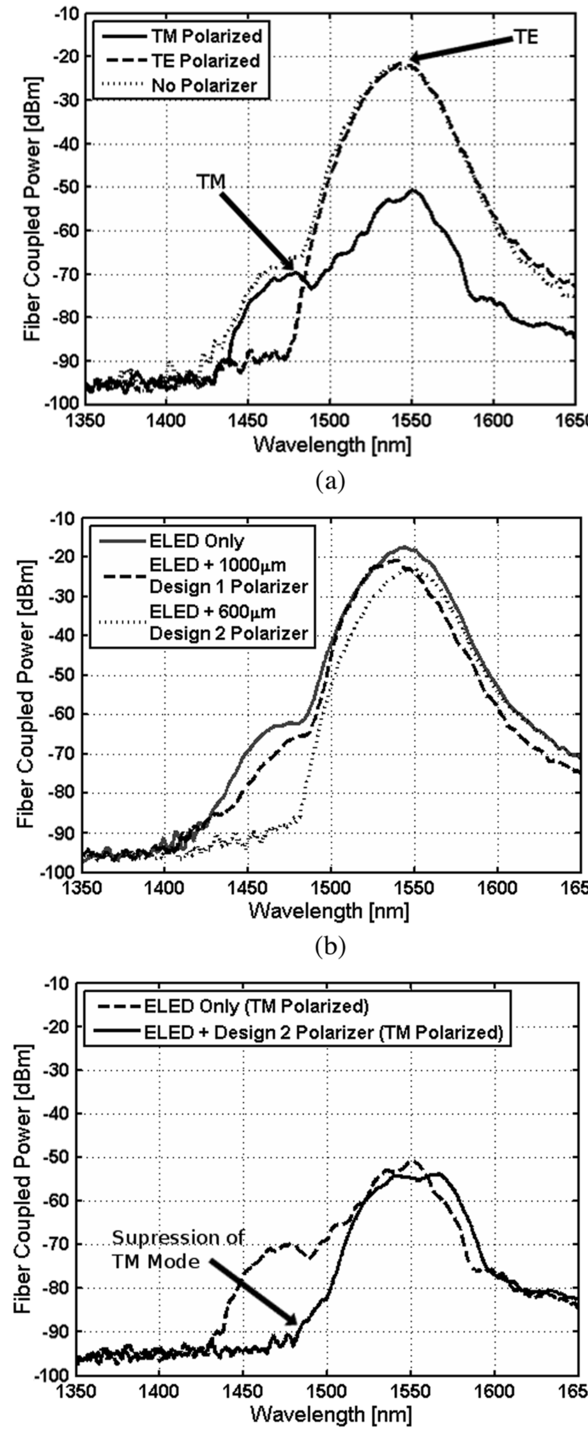

Fig. 3. Output ASE spectra from (a) 1000-μm-long ELED with no on-chip polarizer (resolved for polarization); (b) an ELED only versus an ELED followed by an integrated polarizer; (c) an ELED only versus an ELED and a 600-μm polarizer (Design 2) resolved for TM polarization.

Fig. 3(b) compares the ASE output spectrum of our standard ELED device with those incorporating an integrated polarizer. Clearly, a polarizer using Design 1 does not improve the polarization extinction of the device, which remains at about 44 dB. In contrast, when the ELED is paired with a polarizer of Design 2, the TM peak at 1478 nm is significantly suppressed. The TM-resolved spectra [Fig. 3(c)] for these two devices demonstrate that a polarizer employing Design 2 begins absorbing wavelengths around 1525 nm, and demonstrates a 20-dB improvement in polarization extinction at the TM peak power (1478 nm). Therefore, the polarization extinction between the TE and TM peak powers approaches 63 dB, with a TM peak power of about -87 dBm and a TE peak power of -24 dBm. Additionally, we experimented with applied biases on the polarizers to enhance the selective TM absorption, but found no improvement in polarization extinction levels with either design. It is apparently sufficient to simply probe the polarizer to provide a path for generated carriers to escape.

The difference in polarization extinction between the two polarizer designs is explained in terms of the placement of their respective PL peaks relative to the peak emission wavelength of the ELED. Because $\lambda_{\rm PL}$ of Design 1 occurred at the same wavelength as the peak emission of the ELED, the lowest energy CB states (near $k = 0$) of the polarizer were likely filled due to the high quantity of incident photons. This band filling effect would increase the dominant absorption energy of the polarizer (i.e., to states with $k > 0$). As shown in [7], when the k-vector corresponding to absorption/emission in tensile wells increases, the TM matrix element (which is related to the transition strength) is reduced. In fact, for high enough k values, the TM matrix element can fall to the same level as the TE matrix element, creating a situation in which TE absorption is just as likely as TM absorption. This scenario agrees with the data in Fig. 3(b) for Design 1, as a nearly equivalent reduction in power is seen at the major TE (1550 nm) and TM (1478 nm) emission peaks of the ELED. In the case of Design 2, $\lambda_{\rm PL}$ was shifted to 1515 nm, where the ELED output power is more than 10 dB below the peak power at 1550 nm, suggesting that the degree of band filling in this polarizer would be substantially lower than that of Design 1. With fewer filled states, the TM matrix element would remain larger than the TE matrix element and more TM absorption would occur. As further evidence of this phenomenon, we compared the absorbed photocurrent from the ELED into a 600-μm polarizer (no applied bias). Design 1 absorbs almost 13X as much photocurrent as Design 2 (4.7–0.37 mA), which can be explained if it exhibits significantly greater TE absorption than Design 2.

Fig. 4 shows the effect of polarizer length on the polarization extinction for Design 2. Although the TM peak power does tend to decrease with increased polarizer length, so does the TE peak power. For example, the peak TE power with a 600-μm polarizer falls from -22 to -29 dBm for a 1000-μm polarizer. Because there is no significant improvement in polarization extinction, the polarizer length should be kept below 600 μm to avoid excessive insertion loss. Fig. 4 also shows that the TE peak power for an ELED is about 5 dB higher than that of a device with a 600-μm polarizer. Because the matrix elements for CB-LH transitions permit some TE absorption, a reduction in output power is expected. However, some of this loss can be attributed to the difficulty of coupling output light through our setup and into an optical spectrum analyzer. Since our ELEDs are capable of generating 16 dBm of continuous-wave output power at higher biases [4], this loss is still acceptable for device applications.

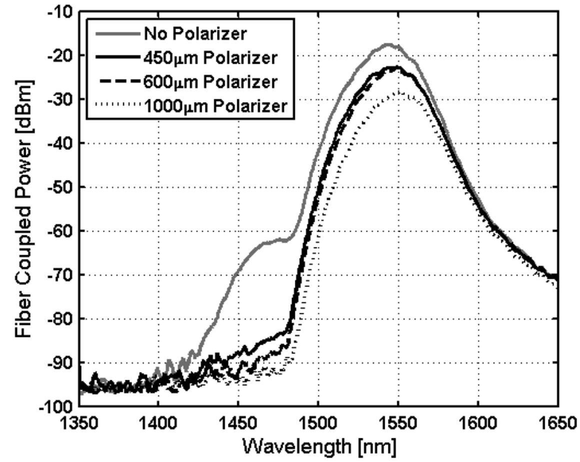

Fig. 4. ASE spectra for a 1000-μm ELED without an on-chip polarizer and with on-chip polarizers (Design 2) of various lengths.

IV. Conclusion

By pairing a compressively strained ELED with a tensile strained polarizer, we have demonstrated the highest reported polarization extinctions from a single-chip InGaAsP–InP broadband emitter. This configuration yields polarization extinctions >60 dB with insertion losses less than 5 dB. This technology is extendable to a variety of PIC applications, including single-chip high-sensitivity fiber-optic gyroscopes.

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