Balanced Operation of a GaInAs/GaInAsP Multiple-Quantum-Well Integrated Heterodyne Receiver

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Abstract—**We describe the balanced operation of a multiple-quantum-well balanced heterodyne receiver photonic integrated circuit (PIC). Using only SMA-connected 50 Ω commercial electronics, we achieve a free-space beam sensitivity of −42.3 dBm at 108 Mb/s and −39.7 dBm at 200 Mb/s for NRZ FSK reception. This represents a 14 dB improvement over any previous heterodyne receiver PIC sensitivity. In addition to providing the multi-channel benefits of heterodyne reception, this is also the highest sensitivity yet reported for any OEIC receiver.**

INTEGRATED optical heterodyne receivers, incorporating continuously tunable local oscillator (LO) lasers, directional couplers, and photodetectors, offer the potential for dramatic simplification of coherent lightwave technology by eliminating packaging of the corresponding discrete devices [1], [2]. Due to the stable, short path-length, and very small reflections which are possible in photonic integrated circuits (PIC's) of this type, isolators may also not be required.

The only previous demonstration of an operative heterodyne receiver PIC had a free-space beam sensitivity (after the focusing objective) of −28.4 dBm at 10^{-9} BER for a 105 Mb/s, $2^{15} - 1$ pseudorandom NRZ FSK signal [1]. In that work, a single integrated multiple-quantum-well (MQW) waveguide detector was used in an unbalanced configuration. In this letter we demonstrate the first balanced operation of a heterodyne receiver PIC. Using only readily available SMA-connected 50 Ω components outside the PIC, we obtain a free-space beam sensitivity of −42.3 dBm at 10^{-9} BER for a 108 Mb/s, $2^{15} - 1$ pseudorandom NRZ FSK signal, and a −39.7 dBm sensitivity at 200 Mb/s. This represents a 14 dB improvement, and careful accounting for departures from the shot- or quantum-noise detection limit suggest that the PIC suffers no major additional penalties beyond the obvious coupling onto the chip and modest chip losses.

The MQW balanced heterodyne receiver PIC is shown in Fig. 1, and has been previously described elsewhere [1]. The InGaAs/InGaAsP device was grown entirely by atmospheric pressure organo-metallic vapor phase epitaxy. The four-section MQW-DBR we employ here offers continuous access to a ~60 Å (750 GHz) tuning range at 1.53 μm. Thresholds are 20–35 mA. The 180 μm-long MQW waveguide detectors employ the same QW's used as the gain medium in the laser. The laser and detector employ buried heterostructure (BH) guides with a SI-InP blocking layer sequence for good current confinement and/or low capacitance. The parallel input port, directional coupler switch, and *S*-bend feeds employ SI-InP clad buried rib (BR) guides for low loss and carefully controlled modal characteristics. Connections between all guides and devices are vertically and laterally self-aligned using a variant on a previously described integration process PPro-2 [3]. The switch used on this PIC is a zero-gap $\Delta\kappa$ design using free-carrier injection laterally outside the switch core to affect switching. The device used for the data described here had a coupling ratio 1.2 : 1 with no current, which was deemed adequate for balanced operation. A photograph of the bonded 3 mm PIC is shown in Fig. 2.

The architecture of the external 50 Ω electronics used in the narrow deviation FSK receiver is shown in Fig. 3. The stud shown in Fig. 2 is mounted such that two SMA center pins contact the back two ceramic stand-offs which have bond wires to the detector pads on the PIC. Commercial 50 Ω bias-tees allow a dc return for the photocurrent from the unbiased detectors which have a capacitance-limited bandwidth of ~1.2 GHz. The signal is thus capacitively coupled in each arm to separate "front end" 2.9 dB noise figure 50 Ω amplifiers with 1 GHz bandwidths and identical 25.3 dB gains, and the signals are then subtracted in a 180°-shifted splitter/combiner. All components in this "front end" were flat to better than ± 0.2 dB in power and ± 2° in phase across the 300–900 MHz band, including any deviations from the splitter and its nominal 180° shift value. Following a 50 Ω amplifier/variable attenuator chain, the signal splits through a directional coupler at the discriminator, with a variable path length in one arm, feeding a RF mixer for discrimination. A bias-tee at the mixer output capacitively coupled the signal to further amplification, and the signal is finally filtered with a 130 MHz filter for the 200 Mb/s case and a 80 MHz filter for the 108 Mb/s case. The low-pass of the bias-tee is used in a feedback circuit to tune the LO for automatic locking of the LO to the incoming signal at an IF specified by the variable delay in the discriminator [4].

It should be noted that the architecture used here has separate amplification for each arm of the balanced receiver to

Manuscript received March 26, 1990; revised June 6, 1990.
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IEEE Log Number 9037735.

1041-1135/90/0800-0577$01.00

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 2, NO. 8, AUGUST 1990

MULTIPLE QUANTUM WELL BALANCED HETERODYNE RECEIVER PIC

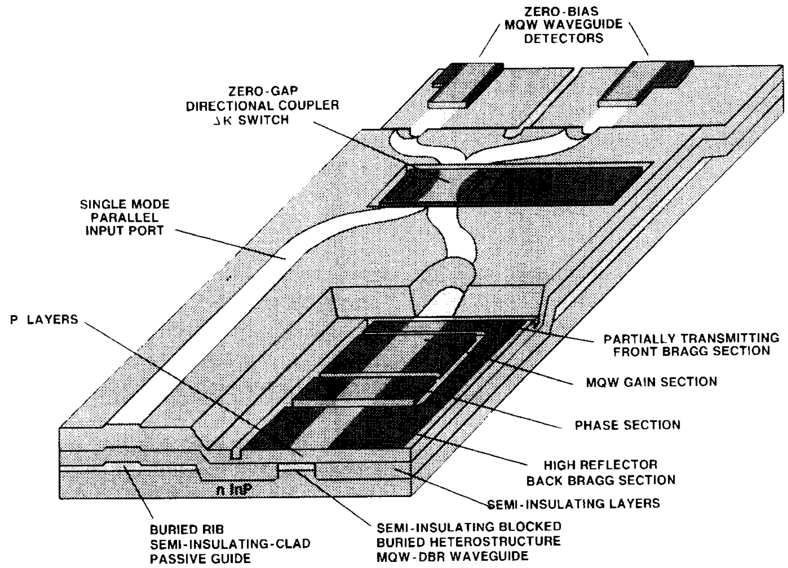

Fig. 1. Configuration of the MQW balanced heterodyne receiver PIC.

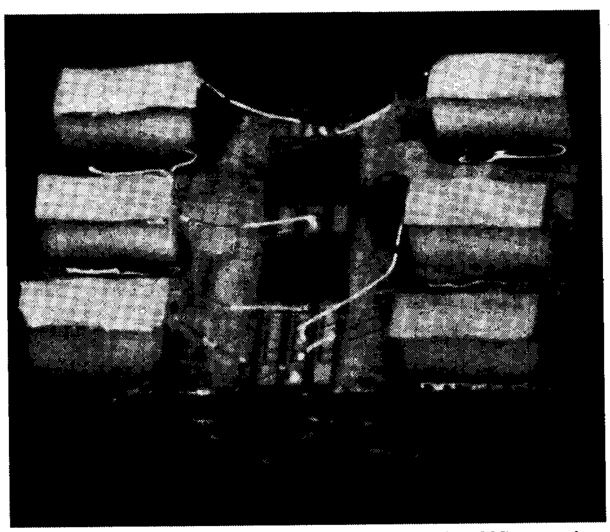

Fig. 2. Photograph of MQW balanced heterodyne receiver PIC mounted on stud.

allow both amplification and impedance matching before the lossy 180° combiner. Due to the smaller signal at each amplifier input, this effectively *doubles* the thermal noise of the front end and electronics when compared to the usual back-to-back diode configuration [5] which provides signal subtraction *before* amplification. The present approach is mandated by the common n-type substrate for the two detectors. The impact of this additional thermal noise will be very small with a higher impedance, high-sensitivity front end, but with the 50 Ω electronics used here it resulted in additional thermal noise penalty.

For a measured combined LO photocurrent at the detectors of 1.40 mA, the calculated shot noise is $i_{\mathrm{SHOT}} = 21.2$ pA/$\sqrt{\mathrm{Hz}}$. The combined thermal noise current from both 50 Ω amplifiers with 2.9 dB noise figures is $i_{\mathrm{THERM}} = 35.5$ pA/$\sqrt{\mathrm{Hz}}$. This leads to an excess thermal noise penalty over shot noise of 5.8 dB, in excellent agreement with the measured 6 dB value seen by observing a 1.3 dB drop in the noise floor when the LO laser is turned off. This also indicates that the balancing has effectively eliminated any noise contribution from the excess intensity noise of the LO laser, which is expected since the common-mode rejection of the present system is estimated to be $\sim$−20 dB.

With an unmodulated input signal the IF beat electrical

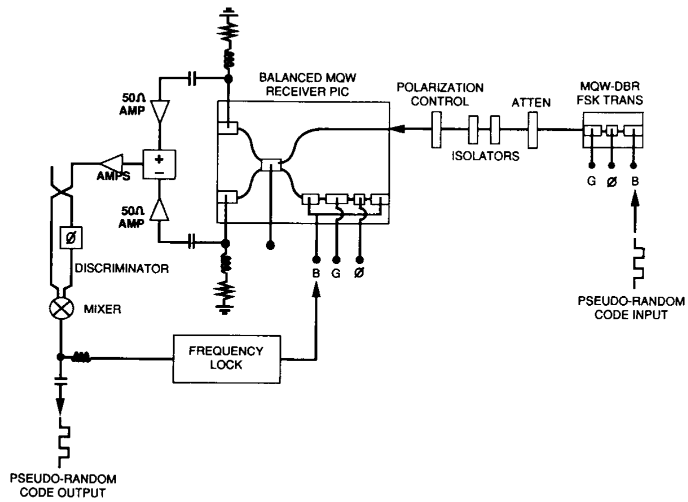

Fig. 3. Configuration of transmitter and electrical layout for evaluation of receiver sensitivity.

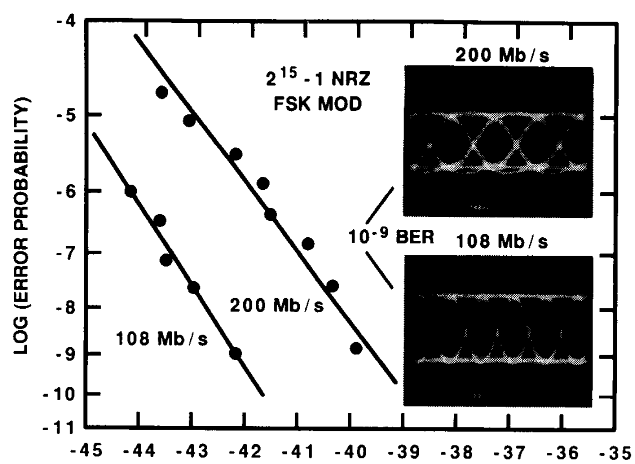

Fig. 4. Bit-error-rate measurements versus free-space optical power outside the PIC at 200 Mb/s and 108 Mb/s, with eye diagrams at 10^{-9} BER in both cases. Sensitivities are −42.3 and −39.7 dBm for 108 and 200 Mb/s, respectively.

power spectrum has a combined −3 dB linewidth of ~13 MHz, and with free-space input beams of several hundred microwatts it rises ~60 dB from the noise floor. It is estimated that the LO laser has a linewidth of ~6 MHz, with an equal contribution from the transmitter laser, which is a three-section MQW-DBR laser [6] modulated through its Bragg section. The combined linewidth value results from the "linewidth floor" of the transmitter and LO lasers, and the high-frequency phase noise in the band of interest may be less than this value would indicate. The measured quantum efficiency of the signal detection in this PIC from a free-space beam outside the chip is 9.3%. The majority of this loss (~6 dB) is coupling loss into the non-AR-coated facet of the parallel input port BR guide using a simple 40 × long-working-distance microscope objective.

Fig. 4 shows the sensitivity data and eye diagrams at 108 and 200 Mb/s, with respective free-space beam sensitivities of −42.3 and −39.7 dBm for a $2^{15}-1$ pseudorandom NRZ code. Very little intersymbol interference is evident in the 108 Mb/s case, while a small penalty is evident in the 200 Mb/s eye. The data shown in Fig. 4 is at $2^{15}-1$ word length, but comparable results were obtained at $2^{23}-1$ word length, indicating good low frequency FM response of the transmitter laser. The IF for this data was set at 600 MHz, and the modulation index for the 200 Mb/s case is $M = 2$, while for the 108 Mb/s case we used $M \approx 3.7$; i.e., the total tone separation in the IF is 400 MHz in both cases.

Table I shows an analysis of the various degradations from the shot noise limit of detection, which is 50 photons/bit for an ideal delay-line discriminator at $M = 2$ [7]. We observe no major degradations beyond the measurable thermal noise from the 50 Ω electronics and obvious coupling losses. This

TABLE I
LISTING OF PARAMETER VALUES IN MQW BALANCED HETERODYNE RECEIVER PIC SENSITIVITY MEASUREMENTS

<table>
<tr><th colspan="6">MQW BALANCED HETERODYNE RECEIVER PIC
200 Mb/s FSK SENSITIVITY BUDGET</th></tr>
<tr><th>ITEM</th><th>VALUE</th><th>CONTRIBUTIONS</th><th colspan="2">DETERMINED BY</th><th>REALIZABLE VALUE</th></tr>
<tr><td>SHOT NOISE LIMIT</td><td>-58.9 dBm</td><td></td><td colspan="2">THEORY (M=2)</td><td>-58.9 dBm</td></tr>
<tr><td>FREE-SPACE TO CHIP COUPLING</td><td>+6.0 dB</td><td>1.5 dB (no AR coat)
4.5 lens focus mismatch</td><td>calc. & est. from prev. results</td><td rowspan="2">MEASURED
total free-space optical power to photocurrent efficiency:
10.3 dB</td><td>+3 dB
(AR coat + lens fiber)</td></tr>
<tr><td>CHIP EFFICIENCY</td><td>+4.3 dB</td><td>1 dB switch rad. loss
1 dB det. BR/BH coupling
1 dB prop. + bend loss
1.3 dB unassigned:
det. η_d, excess loss</td><td>calc. & est. from prev. results</td><td>+3.3 dB ?
(improved BR/BH coupling)</td></tr>
<tr><td>THERMAL NOISE</td><td>+6.0 dB</td><td>noise from both 50Ω amps w/2.9 dB NF</td><td colspan="2">6.0 dB MEASURED
5.8 dB CALCULATED</td><td>< 1 dB
(high-Z front end)</td></tr>
<tr><td>UNASSIGNED</td><td>+2.9 dB</td><td>RF system flatness, transmitter response, imperfect balance, finite LO and trans. $\Delta\nu$</td><td colspan="2">estimated</td><td>+1.9 dB ?
(improve RF and balance)</td></tr>
<tr><td>TOTAL</td><td>-39.7 dBm</td><td></td><td colspan="2"></td><td>~ -50 dBm
fiber power sensitivity</td></tr>
<tr><td>FREE-SPACE SENSITIVITY</td><td>-39.7 dBm</td><td></td><td colspan="2">MEASURED</td><td></td></tr>
</table>

lack of any degradation from LO reflections strongly supports the contention that isolators are not required.

Also shown in Table I are the projected improvements which might be obtained with practical, easily realizable modifications. Chief among these are the use of a higher impedance, lower noise front end, the application of an AR coating, and use of a microlensed fiber for input. This should be able to produce a 200 Mb/s fiber sensitivity of ~−50 dBm, or <400 photons/bit, compared to the highest reported sensitivity of −57.2 dBm for a hybrid 200 Mb/s FSK receiver using a tuned front end amplifier [8]. Even the present free-space values of −42.3 dBm at 108 Mb/s and −39.7 dBm at 200 Mb/s obtained with 50 Ω plug-in electronics represent the highest sensitivity reported to date for any OEIC receiver. However, we believe that the true appeal of coherent technology lies in its channel selectivity for multichannel applications, and PIC's of this type should ultimately make the widespread deployment of such technology feasible.

ACKNOWLEDGMENT

The authors would like to thank B. Glance and O. Scaramucci for valuable assistance in setting up the discriminator and LO frequency locking circuitry.

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