We report implementation of a monolithically integrated 100 Gbps dual-polarization quadrature phase shift keying (DP-QPSK) wavelength tunable coherent receiver on a 1 mm × 3 mm die that consists of a tunable C-Band local oscillator with a 40 nm range, eight 30 GHz photodetectors, and two parallel 90° optical hybrids. A BER of 10^{-3} with an OSNR of 7.5 dB operating at 50 Gbps NRZ-QPSK data per channel is reported.

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the upper LO path using an electro-optic phase shifter, thus producing the quadrature data. The optical signals are then detected in waveguide photodiodes downstream of the MMI outputs; the diodes are single-ended due to a shared n-type substrate ground. The SG-DBR laser consists of a front mirror, back mirror, and phase section with electro-optic phase shifters, a gain section, and an absorber section. The laser is designed with a Bragg wavelength $\lambda_B = 1540$ nm, and the peak spacing is 3.55 and 3.24 nm for the front and back mirrors, respectively. The output of the laser is TE-polarized due to tensile strain on the quantum wells in the gain section. The LO output is split by a $1 \times 2$ MMI and routed to each optical hybrid. A photograph of the fabricated device is shown in Fig. 1(b).

The receiver was fabricated on a semiconducting InP substrate. The epitaxial structure consists of a quaternary waveguide layer with a 1.4 $\mu$m bandgap, a multiple quantum well gain/absorption layer, and a regrown InP upper cladding. The fabrication process consists of eight mask layers and one regrowth. All features except the waveguide gratings were defined using an i-line stepper; the gratings were defined using electron beam lithography. Novel steps in the device fabrication include use of benzocyclobutene (BCB) under the metal contacts of the photodetectors, reduced photodiode contact surface area, and an inductively coupled plasma (ICP) dry etch for the waveguides. A schematic of the fabricated photodetector is shown in Fig. 2. The photosensitive BCB was spun at low revolutions per minute, resulting in a 7.5 $\mu$m thick layer after curing. The metal contacts were defined 14 $\mu$m around the waveguides with a 60 $\mu$m diameter circular pad at one end for wire bonding; total pad surface area is $\sim 4000 \mu$m$^2$. Waveguides were etched into the semiconductor material with an ICP dry etch consisting of chlorine, nitrogen, and argon gas. Line edge roughness of the resulting waveguides was measured to be 20 nm root mean square, which is sufficient for propagation losses lower than 2 dB/mm. The fabricated device was thinned to 150 $\mu$m, cleaved, and soldered to an AlN carrier for improved thermal stability.

The LO was first tested to determine the range of operation, output power, and side mode suppression ratio (SMSR). Tuning range was determined by sweeping the front and back mirror currents from 0 to 40 mA and measuring the output wavelength of the device in an optical spectrum analyzer (OSA); the results of this measurement are plotted in Fig. 3. Typical observed SMSR was $> 48$ dB, with quasi-continuous tuning shown over a 44 nm range from 1520 to 1564 nm. Threshold current was 34 mA. Next, the photodiodes were swept with an optical signal from 100 MHz to 40 GHz using a Keysight lightwave component analyzer to determine RF performance; a normalized response from one of the photodiodes biased at −2 V is presented in Fig. 4, displaying a 30 GHz 3 dB optical bandwidth. All electrical connections up to the coplanar waveguide (CPW) transmission lines were calibrated out of the measurement; the wire bonds and CPW lines were included. Several dips in the response magnitude were due to resonances from ground discontinuities on the CPW lines. Photodiode dark current was 10–15 $\mu$A across all photodiodes with laser and phase sections biased. Resistivity of the diodes was roughly 3000 $\Omega \cdot \mu$m$^2$ measured with on-chip transmission line
Method typically having a resistance of about 27 Ω. Responsivity of the photodiode was 0.3 A/W measured with an off-chip test structure; the measurement includes coupling loss from a lensed fiber with a 2.5 μm spot size to the on-chip waveguide. Net receiver responsivity was measured and is plotted versus wavelength in Fig. 5 for a −1.5 V bias on the photodiodes; the maximum net responsivity was 0.03 A/W at 1513 nm. Useful optical bandwidth of the receiver is over 100 nm. Net responsivity includes 6 dB splitting loss in the hybrid and the responsivity of the photodiodes; thus, the excess loss of the receiver is 4.1 dB or roughly 1.4 dB/mm waveguide loss due to photon scattering from line-edge roughness and inter-valence band absorption in the upper cladding layer.

To verify photodiode operation, an amplitude-shift keying nonreturn-to-zero (NRZ) pseudorandom binary sequence (PRBS) with a pattern length of 2^7 − 1 at 25 GHz was fed into the device and recovered at the positive in-phase (I+) and quadrature (Q+) photodiodes. The optical signal was preamplified to 20 dBm using an erbium-doped fiber amplifier (EDFA) and filtered using a 0.4 nm tunable filter before being coupled into the chip, and the received photocurrent was amplified with an RF amplifier, similar to the setup shown in Fig. 6. Open eyes from both photodiodes are shown as inserts in Fig. 4.

The available LO power was determined by biasing the laser at 191 mA and measuring the photocurrent in the diodes; the LO photocurrents were in the range of 200–300 μA across the photodiodes. The linewidth of the LO was then measured using the self-heterodyne method. The output from the back of the LO was coupled off-chip using a lensed fiber and then split in a 50/50 fiber coupler. One output was delayed with a 20 km length of LEAF fiber, and the other output was shifted 100 MHz using an acousto-optic modulator. The beams were then combined in another 50/50 fiber coupler, converted to an electrical current through a high-speed photodiode, and measured in an electrical spectrum analyzer with a 200 kHz resolution bandwidth. Linewidths (3 dB) of 12, 15, and 18 MHz were measured at 1545.26, 1548.38, and 1551.5 nm, respectively; these linewidths were achieved by tuning only the front mirror of the laser. The increasing trend in linewidth is likely due to increased electro-optic absorption in the mirrors, as each higher wavelength required a 2–3 mA increase in the current to the front mirror. To eliminate reflections from the back facet, which could cause injection locking of the SG-DBR, the absorber section of the laser was reverse biased. At the front of the laser, reflections from the hybrids back into the LO were minimal due to 8 dB of path loss through the waveguide bends, resulting in 16 dB total return loss. An external cavity laser with a 100 kHz linewidth was coupled with the on-chip LO using the on-chip hybrid, and the RF spectrum of the resulting beat frequency was measured from one of the photodiodes. The 3 dB linewidth of the beat tone was 130 MHz, which is much larger than the linewidth of the individual lasers, due to significant 1/f noise of the two lasers from thermal fluctuations and vibrations. The beat frequencies detected in the I+ and Q+ photodetectors were then viewed simultaneously with a real-time oscilloscope, and the phase path of the lower half of each hybrid was tuned so that the beat frequencies were 90° out of phase, thus ensuring quadrature encoded data recovery. A 50 Gbps NRZ phase-shift keying (QPSK) signal generated from two individual PRBS 2^7 − 1 data streams was used to test individual channel operation; the test setup is shown in Fig. 6.

A polarizing beam splitter cube was used before the receiver inputs to separate incoming polarization-multiplexed signals; the transverse-electric (TE) path was fed directly to one channel, while the transverse magnetic (TM) signal was rotated to the TE orientation using a polarization controller before being fed to the other channel for compatibility with the LO signal. The optical signal was again preamplified to 20 dBm using an E DFA and filtered with a 0.4 nm tunable filter before being coupled into the chip, and the received photocurrents were amplified with an RF amplifier and processed using a Keysight optical modulation analyzer (OMA). The OMA contains a digital signal processor (DSP), which performed equalization, clock recovery, carrier phase estimation, decoding, and error detection. Three different wavelengths were tested to verify receiver operation, and the resulting bit error rate (BER) versus the optical signal-to-noise ratio (OSNR) of the input signal is presented in Fig. 7.

An error floor was measured at 10^-8 for all three wavelengths, likely due to the 130 MHz linewidth of the beat tone. A BER of 10^-3 was achieved at an OSNR of 7.5 dB for the 1548.38 and 1551.5 nm wavelengths, while an OSNR of 11.5 dB was required to achieve the same BER at 1545.26 nm. This difference can be attributed to the carrier phase estimation algorithm implemented in the DSP, which uses a Kalman filter to compensate for the phase noise of the beat tone and determine the phase of the signal. At 1545.26 nm, the LO linewidth was narrow enough that the phase estimation could be set low, resulting in less phase distortion of the recovered signal, as shown in the recovered constellation in Fig. 8. At 1548.38 and 1551.5 nm, the linewidths required more aggressive phase estimation, resulting in increased phase distortion of the recovered constellations. A secondary effect was an improvement in the measured BER versus OSNR at these wavelengths, as the phase estimation likely caused minor error correction of some of the errors from noise in the incoming signal, resulting in a measured BER exceeding the theoretical limit for a nonerror-corrected signal at the lower OSNR points.
have been demonstrated with 200–300 kHz linewidths over a 40 nm tuning range by eliminating the current injection in the mirror sections [13], and electronic feedback from an asymmetric Mach–Zehnder has been used to reduce an SG-DBR laser linewidth from 19 MHz down to 570 kHz [14] with theoretical capability below 100 kHz. Additionally, integrated optical phase locking would eliminate the low frequency drift between the carrier and LO and has been demonstrated on a heterodyne receiver with an integrated SG-DBR [15]. Other work includes on-chip integration of polarization splitting and electrical amplifier functions to further reduce system complexity, use of total internal reflection mirrors on the LO path to increase available LO power in the photodiodes, and a directional coupler-based 90° optical hybrid to minimize injection locking of the LO due to reflections.

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**REFERENCES**