RIE Lag Directional Coupler based Integrated InGaAsP/InP Ring Mode-locked Laser

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We have demonstrated the first integrated ring mode-locked laser (MLL) with a reactive ion etch (RIE) lag coupler. The RIE lag directional coupler (RL-DC) is highly advantageous for integrated MLLs as it has an insertion loss <1 dB and can be designed to provide any coupling value. This provides the RL-DC with a much needed flexibility in large photonic systems unlike standard multimode interference (MMI) couplers, which typically provide only 3 dB power splitting.

InGaAsP/InP MLLs operating at a 1.55 µm wavelength are very stable pulsed sources, which makes them attractive components for high-speed optical fiber communication with optical-time-division-multiplexing (OTDM) [1], multi-wavelength sources for wavelength-division-multiplexing (WDM) [2], and clock distribution systems [3]. MLLs built on a highly versatile InGaAsP/InP material platform provide the capability to create monolithically integrated systems-on-chip. Previously, Y. Shi has demonstrated a single RIE lag directional coupler defined by electron-beam lithography [4]. To allow ease of fabrication of the current MLL device in large photonic integrated circuits (PICs), we have defined the entire structure using i-line stepper lithography and a single etch.

A standard offset quantum well (OQW) InGaAsP/InP integrated platform was used with 7 QWs positioned above a 300 nm tall 1.3Q waveguide with a confinement factor of 7.1%. A wet-etch removes the QWs for low loss passive waveguides followed by a single blanket p-cladding regrowth. Waveguides were defined by stepper lithography on a photoresist/Cr/SiO_2 three-layer mask. The patterned SiO_2 mask was used to mask the InGaAsP/InP in Cl_2/H_2/Ar etch chemistry with Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE). The RIE lag effect, which acts to slow the etch rate of smaller features, was used to define a 300 µm long 700 nm wide directional coupler on a deeply etched 4400 µm ring with a single etch-step, as shown in Fig. 1. The directional coupler has an etch depth of ~2.65 µm (100 nm from the bottom of the waveguide), while the deeply etched waveguides have an etch depth of 3.6 µm (below the waveguide layer by 850 nm), as shown in Fig. 2. A deeply etched directional coupler requires an extremely narrow gap <200 nm to have appreciable coupling. This typically requires more complicated Electron-Beam-Lithography (EBL), while the severe RIE lag effect from the narrow feature necessitates long etch times. This etch is difficult to make vertical and smooth, which increases scattering losses. We overcome these issues by adopting the single-etch process, which uses the RIE lag to our advantage and allows more streamlined processing of directional couplers without the need for a separate surface ridge waveguide defined by wet-etching and deeply etched waveguide defined by dry-etching.

As shown in Fig. 3, the measured cross coupling of the RIE lag directional coupler varies from 7-to-10% over the telecom C-band. The measured peak power off-chip was ~200µW (-7 dBm). The RF spectra of the fundamental and second harmonic from ESA measurements is shown in Fig. 4. The raised plateau on the RF spectra at 3 GHz is due to distortion from a low noise amplifier in the ESA and appears regardless of signal. The MLL shows stable operation over a wide range of SA biases -8 to -3 V and Semiconductor Optical Amplifier (SOA) drive currents of 170-290 mA. The mode-locked regime with RF power >25 dB above the noise is shown in Fig. 5. The pulse width variation measured by an Inrad SHG autocorrelator (AC) is shown in Fig. 6. The minimum pulse width is 1.1 ps with a spectral width of ~6 nm.

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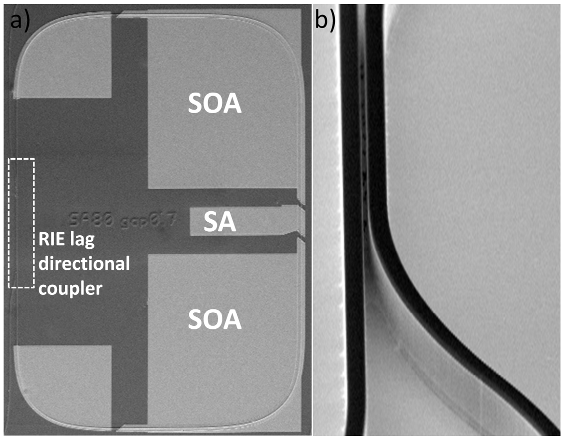

Fig. 1. Top-down SEM image of a) fabricated ring mode-locked laser and b) RIE lag directional coupler.

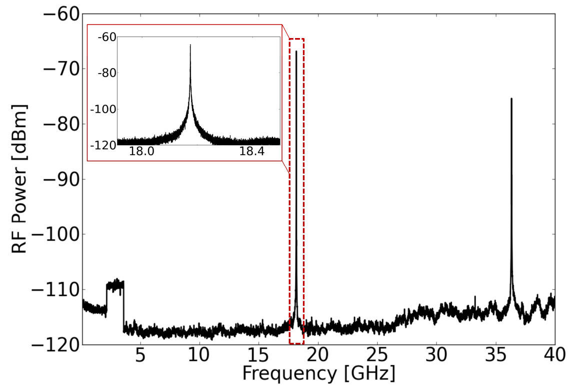

Fig. 4. ESA RF power spectrum at mode-locking showing first and second harmonic. Due to the low input power, the input electrical signal passes through a 30 dB low noise amplifier (LNA). The pedestal seen at 3 GHz is an artifact due to the LNA.

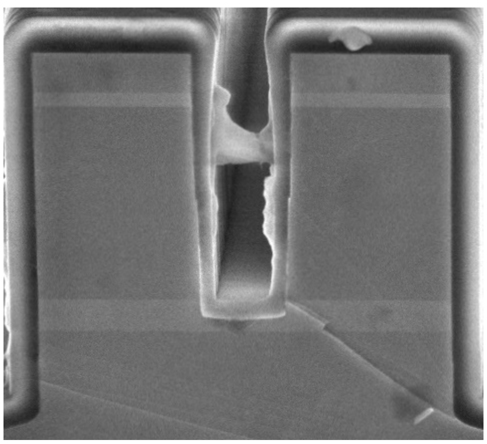

Fig. 2. SEM image of RIE lag directional coupler cross-section. The center etch depth is 200 nm into the waveguide layer.

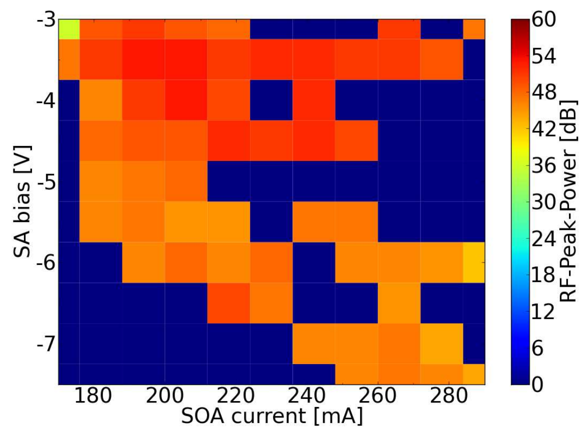

Fig. 5. Measured RF power of the MLL over the operating regime.

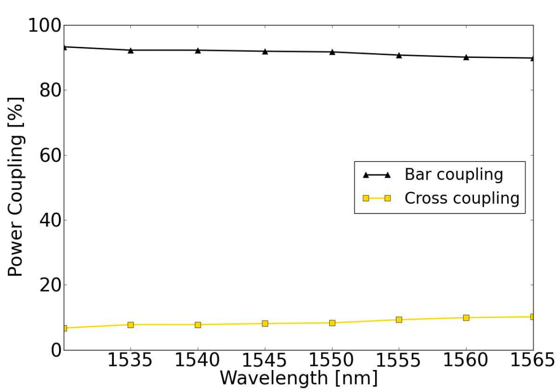

Fig. 3. Measured bar and cross coupling of 300 μm long RIE lag directional coupler. Insertion loss was measured at <1 dB.

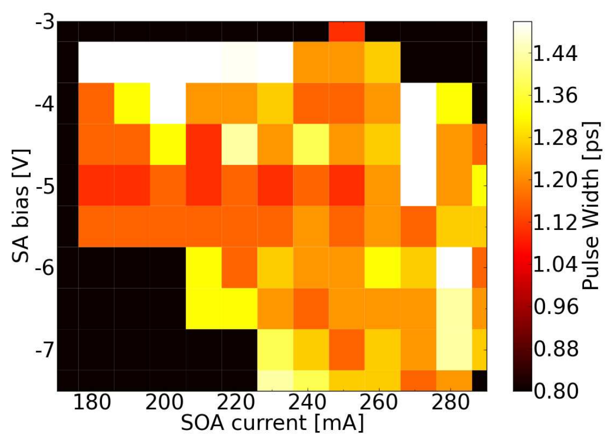

Fig. 6. Measured pulse width of the MLL over the operating regime.