Fundamental and Subharmonic Hybrid Mode Locking of Semi-assembled Semiconductor Ring Laser in InP Generic Foundry

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ABSTRACT

We report on 12.5-GHz microwave generation via passive, fundamental and subharmonic hybrid mode-locking of a foundry-fabricated ring laser IC on a RF-compatible submount. The 200-kHz RF linewidth for PML is greatly reduced to Hz-level for HML, and 25-dB single-sideband phase-noise suppression for 15-dBm RF injection power is achieved. In subharmonic HML, the compromise between supermode intensity and phase noise is analyzed.

Keywords: photonic integrated circuits, mode-locked lasers, microwave photonics

Electrically driven monolithically integrated semiconductor passively mode-locked lasers (PMLL) offer a simple, compact, cost-effective and power-efficient solution to high-purity microwave generation. Phase noise and timing jitter of generated signal can further be improved by using hybrid mode-locking (HML) technique, where an electrical modulation is injected into saturable absorber of the PMLL at the resonant frequency that the PMLL is locked at. Although direct modulation at the fundamental frequency corresponding to the cavity round-trip rate is the most straightforward approach, the maximum frequency is limited to around 40 GHz due to the bandwidth of driving electronics [1,2]. However, >40-GHz bands have recently attracted attention as millimeter wave (mmW, 30 – 300 GHz) and terahertz (THz, >300 GHz) signals are promising for the next generation high-speed transmissions to deliver Gb/s data rate [3]. For this purpose, to generate stable and higher repetition-rate signal using lower frequency driving electronics is highly desirable. In this paper, we present a proof-of-concept implementation of fundamental and subharmonic HML of a foundry-fabricated semiconductor laser at 12.5 GHz. The InP photonic integrated circuit (PIC) chip is assembled with a specifically designed RF submount to support GSG (Ground-Signal-Ground) high frequency electrical feed. The signal purity and locking characteristics in terms of linewidth and single-sideband (SSB) phase noise are experimentally investigated.

The ring-geometry semiconductor laser used for fundamental and subharmonic HML is shown in Fig. 1. The ring cavity is 6.5-mm long corresponding to a repetition rate of 12.5 GHz. The cavity is composed of one 30- µm saturable absorber (SA) surrounded by two 400-µm gain sections (SOA, semiconductor optical amplifier) and 4-mm electro-optic phase modulator (EOPM) in four sections and passive waveguides/components. One 3-dB 2x2 MMI coupler guides the optical signals out of the ring cavity. The upper MLL is characterized by forward biasing the two SOA sections with a gain current (I_{SOA}) and biasing the SA with a hybrid RF-DC reverse voltage via a bias-tee (V_{SA}), as shown in Fig. 2. The signal from the waveguide output (Out) is collected with a lensed fiber and sent to electrical spectrum analyzer after a high-speed photodiode.

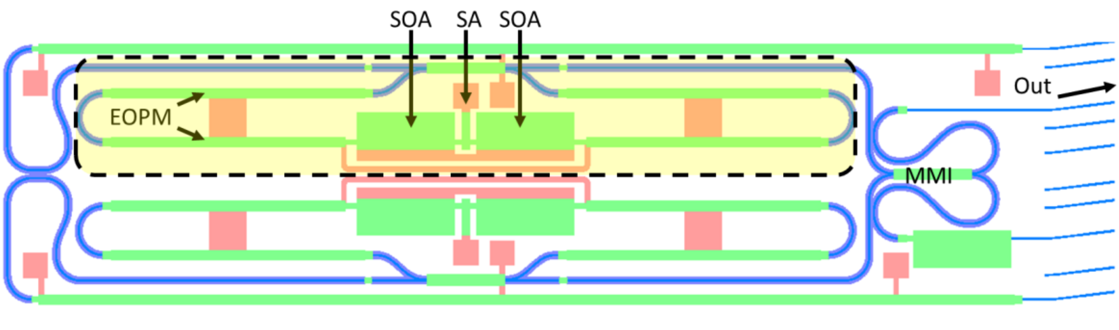

Figure 1. Schematic layout of the proposed PIC. Red: metallization layer. Green: active components (SOA and EOPM) and passive components (MMI coupler). Blue: deeply and shallowly etched waveguides.

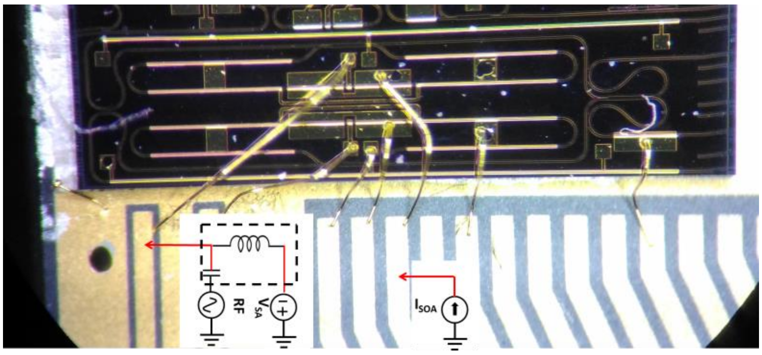

Figure 2. Microscope photograph of the semi-assembled PIC and the specifically designed RF submount. The InP chip is wire-bonded and physically placed onto the RF submount. One RF GSG probe and one DC probe are used to bias the SA and SOAs, respectively.

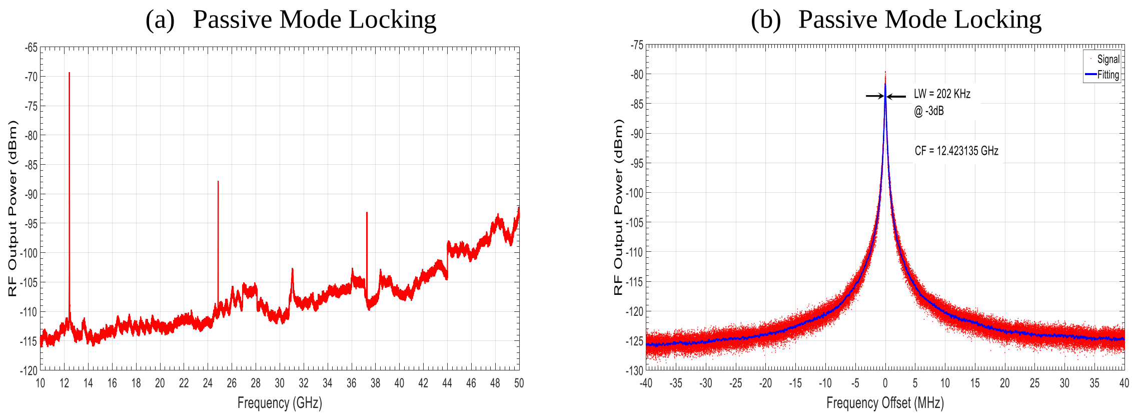

Figure 3. (a) Full-span (50 GHz), and (b) Close-up view of the RF spectrum of the MLL in PML. (I_{SOA} = 94 mA, V_{SA} = 2.35 V). Center Frequency (CF) = 12.423 GHz. 3-dB linewidth (LW) = 202 kHz.

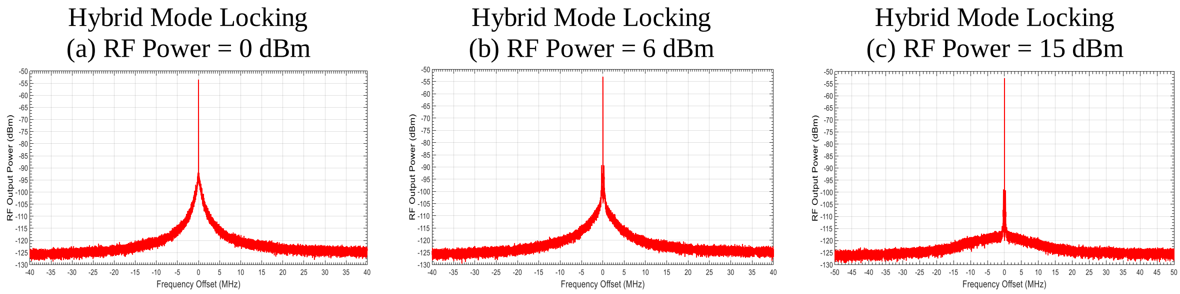

Figure 4. Close-up view of the RF spectrum of the MLL in fundamental HML. (I_{SOA} = 94 mA, V_{SA} = 2.35 V, RF Frequency = 12.423 GHz) for (a) RF Power = 0 dBm, (b) RF Power = 6 dBm, (c) RF Power = 15 dBm.

The down-converted RF spectrum of the MLL in PML for I_{SOA} = 94 mA and V_{SA} = 2.35 V is depicted in Fig. 3. In Fig. 3(a), three harmonic components are present at 12.5, 25, and 37.5 GHz. With a Lorentzian function, the 3-dB linewidth is estimated to be 202 kHz and the center frequency is found at 12.423 GHz in Fig. 3(b). The beat-note frequency is slightly tuneable by varying the bias condition and phase modulator voltage. In the close-up spectra shown in Fig. 4 the base and floor are reduced for higher RF injection power and subsequently a greater suppression ratio is achieved.

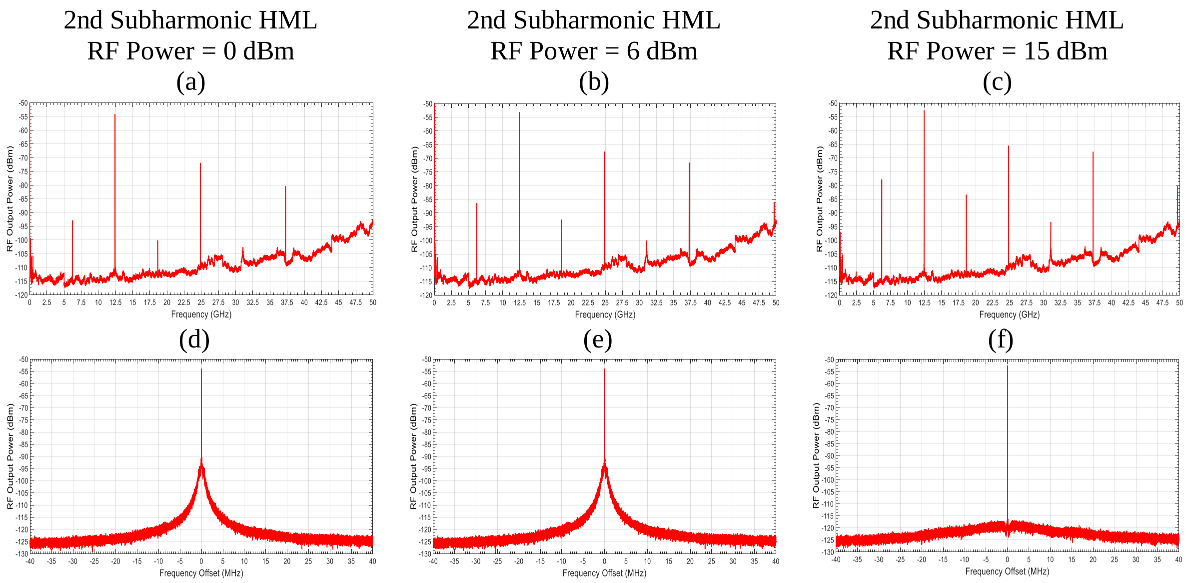

Figure 5. Full-span and Close-up view of the RF spectrum of the MLL in 2nd subharmonic HML. (I_{SOA} = 94 mA, V_{SA} = 2.35 V, RF Frequency = 6.212 GHz) for (a),(d) RF Power = 0 dBm, (b),(e) RF Power = 6 dBm, (c),(f) RF Power = 15 dBm.

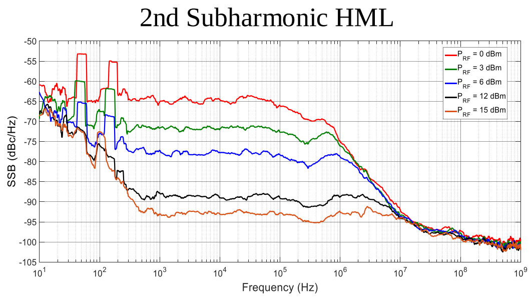

Figure 6. (a) SSB phase noise of the MLL in fundamental HML. (I_{SOA} = 94 mA, V_{SA} = 2.35 V, RF Frequency = 12.423 GHz) for RF Power = 0, 3, 6, 12, and 15 dBm. (b) SSB phase noise of the MLL in 2nd subharmonic HML. (I_{SOA} = 94 mA, V_{SA} = 2.35 V, RF Frequency = 6.212 GHz) for RF Power = 0, 3, 6, 12, and 15 dBm.

Figure 5 shows a series of full-span RF spectra and close-up RF spectra in second subharmonic HML for RF power = 0, 6, and 15 dBm, RF frequency = 6.212 GHz. The supermodes at odd multiple of the RF modulation frequency (6.212 GHz, 18.626 GHz, and 31.060 GHz) grow for higher RF injection power. The associated supermode noise resonances may negatively affect the phase noise at the sidebands of the RF resonance peak giving rise to timing jitter. Similarly, a greater signal-to-noise ratio is obtained for greater RF power. There is a trade-off between supermode intensity and RF signal-to-noise ratio. Figure 6 shows the evolution of single side-band (SSB) phase noise for a range of different RF power in fundamental HML. For RF power = 15 dBm, the SSB phase noise is significantly reduced by 25 dB within 10^3 – 10^5 Hz and not affected when the offset frequency is larger than 10^7 Hz. In conclusion, we have demonstrated the passive, fundamental and subharmonic hybrid mode locking of InP foundry-fabricated semiconductor ring laser on RF submount that supports high frequency electrical driving. The RF spectrum, beat-note linewidth, phase noise as well as supermode are analysed. The approach can be deployed for stabilized mmW generation using cost-effective photonic and affordable electronic devices.

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