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A Complete Monolithically-Integrated Circuit for All-Optical Generation of Millimeter-Wave
Frequencies

G. Allen Vawter, Alan Mar, Vince Hietala, John Zolper

Sandia National Laboratories, Albuquerque, NM 87185-0603, USA

(505) 844-9004, (505) 844-8985 fax

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A optoelectronic integrated circuit for generation of mm-wave frequencies is demonstrated and design issues detailed. A monolithically integrated ring laser, optical amplifier and photodiode generate electrical signals up to 85.2 GHz.

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A Complete Monolithically-Integrated Circuit for All-Optical Generation of Millimeter-Wave Frequencies

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Sandia National Laboratories, Albuquerque, NM 87185-0603, USA
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All optical generation of mm-wave signals has the potential for dramatic improvements in efficiency compared to current solid-state electronic sources, such as negative-differential-resistance diodes, at frequencies well above 60 GHz. The high quantum efficiency of passive mode-locked diode lasers and rib waveguide optical amplifiers coupled with the power-handling capability and efficiency of traveling-wave photodiodes¹⁻³ (TWPD) suggests that mm-wave source with 30 to 50% efficiency and greater than 10 dBm output at frequencies up to 200 GHz is a possibility.

We demonstrate the first such compact optoelectronic integrated circuit (OEIC) for generation of mm-wave frequencies. This new OEIC integrates a passively mode-locked semiconductor ring laser⁴, optical amplifier and high-speed photodiode for generation, amplification and detection of an optical pulse train with 30 to 90 GHz pulse-repetition frequency. Output of the OEIC is an electrical signal, generated by the photodiode, whose fundamental frequency is the pulse repetition rate of the mode-locked laser. Such lasers have been demonstrated up to 172 GHz pulse repetition frequency. The circuit uses a novel waveguide photodiode (WGPD) integrated with a mm-wave transmission line specifically designed for high-speed operation and signal extraction on a heavily-doped GaAs substrate. Issues influencing the design of the WGPD and transmission line will be presented.

The mm-wave generation OEIC (Fig. 1) uses (Al,Ga)As double-heterostructure rib waveguides with a single-quantum-well active region. Multi-lateral-mode ring waveguides with Y-junction output couplers are etched to form passively mode-locked lasers monolithically integrated with an optical amplification section and WGPD at the laser output. Pulse repetition frequency is fixed by the ring diameter and saturable absorber configuration; we have demonstrated 30, 60 and 90 GHz circuits. The WGPD is formed using a trench etch around the rib waveguide and is integrated with an electrical transmission line for efficient removal of the output signal. The WGPD was chosen instead of an electrically distributed TWPD so that the photodiode would use the same epitaxial material as the laser and amplifier. Figure 2 shows cross sections of all parts of the circuit including the 50 Ohm transmission line used for signal extraction from the WGPD.

The RF output spectrum of each OEIC is plotted in Fig. 3. Fundamental pulse repetition frequency of the 860, 430 and 290 μm diameter of rings were 29.1, 57.5 and 85.2 GHz respectively. Frequency generation close to the desired value was achieved for all three laser diameters. The observed linewidth is dominated by the approximate 900-psec rms pulse-to-pulse timing jitter. Such values are not unusual for passively mode-locked semiconductor lasers. Peak mm-wave power levels are -12, -23 and -27 dBm at 29.1, 57.5 and 85.2 GHz respectively.

This circuit demonstrates the feasibility of mm-wave signal generation using a mode-locked ring laser OEIC. Output power of these circuits is influenced by a number of factors including the internal circulating power of the ring, the amount of power coupled out of the ring, the gain of the amplifier, and the efficiency of the photodiode. Efficiency of the photodiode is limited to 10% at the highest frequencies due to the short length required for low-capacitance and high-speed operation. A TWPD would improve the output power tenfold although epitaxial regrowth of the TWPD may be required to achieve the correct *pn*-junction depletion width for velocity-matched operation. Optimizing the output coupler for power extraction from the ring and using a flared

amplifier with one or more photodiodes operating in parallel at the wide amplifier output end may result in further power enhancements by as much as a factor of 100. Some possible configurations of an improved OEIC for higher-power operation will be discussed.

In summary, we have demonstrated a new type of OEIC for direct generation of mm-wave frequencies. This OEIC integrates a passively mode-locked semiconductor ring laser with an optical amplifier and high-speed waveguide photodiode. OEICs using this concept could be used in a wide variety of applications where a very compact, lightweight mm-wave source is required. This work was supported by United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy.

Figure 1: Schematic view of millimeter-wave generation OEIC. L is WGPD length and d is the ring laser diameter.

Figure 3: Measured electrical output spectrum of three different millimeter-wave generation OEICs. Ring laser diameter determines the output frequency of circuit.

(a) n^+ GaAs Substrate

Figure 2: Cross section diagram of laser and amplifier, (a), WGPD, (b), and transmission line, (c).

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