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Ultra-fast Compact Modulator-Integrated-VCSEL for Highly Efficient Millimeter-wave Modulation

Hamed Dalir and Fumio Koyama

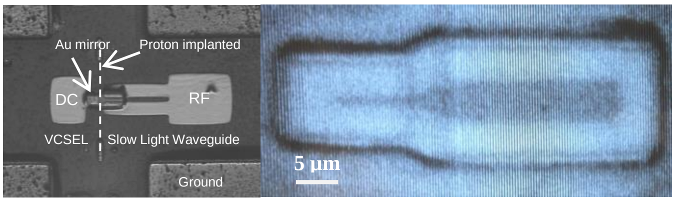
[1]Photonics Integration System Research Center, Tokyo Institute of Technology
4259-R2-22 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan
dalir.h.ac@m.titech.ac.jp

INTRODUCTION

The Radio-over-fiber (ROF) links, which integrate fiber optics and wireless radio communication systems, have been attracting key role to offer broadband wireless services [1-4]. On the contrary, vertical cavity surface emitting lasers (VCSELs) have been well realized for short reach applications [5,6]. Low power consumption, small footprint, wafer-scale testing, low-cost packaging, and ease of fabrication into arrays are some of the merits of VCSELs. In addition to them, VCSELs propose low cost package for indoor applications. In this paper, a compact electro-absorption slow-light modulator laterally-integrated with an 850 nm VCSEL for millimeter-wave modulation is presented.

STRUCTURE

The top view and infrared image of oxide aperture of the fabricated device (slow-light modulator-integrated VCSEL) is shown in Fig.1 (a) and (b), respectively. The vertical structure is the same as that of conventional 850 nm VCSELs. The bottom mirror consists of a 35-period Si-doped $Al_{0.9}Ga_{0.1}As/Al_{0.15}Ga_{0.85}As$ DBR. The active region has three $Al_{0.3}Ga_{0.7}As/GaAs$ quantum wells sandwiched in one-λ cavity. The top mirror consists of a 22.5-period carbon-doped $Al_{0.9}Ga_{0.1}As/Al_{0.15}Ga_{0.85}As$ DBR. Lateral optical confinement is formed by applying an oxide layer, while widening the waveguide width with a taper shape guides a strong leaky travelling wave in the lateral direction from the VCSEL into an electro-absorption modulator. It is noted that the width of the slow light waveguide functions as a MMI coupling, thus we are able to form a quasi-unidirectional coupling to the slow light waveguide (the details would be discussed elsewhere).



(a) (b)

Fig. 1(a) Top view of the fabricated device, and (b) infrared image of oxide aperture

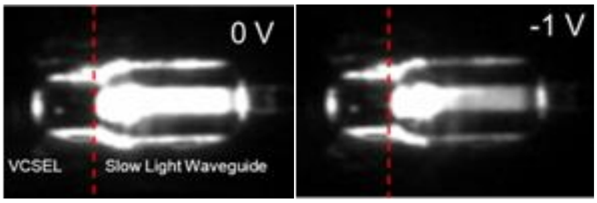


Fig. 2 (a) The near-field patterns for different modulator voltages (un-changed intensity in the slow light waveguide is the proton implanted region).

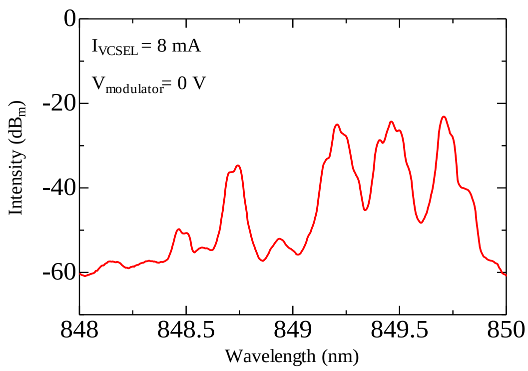


Fig. 3 Measured emission spectrum for the bias of 0 V of the modulator section far from the proton implanted region.

RESULTS

Figure 2 illustrates the near field pattern for the on and off states by applying reverse bias of 0 and 1 V in the modulator side, respectively. While the top emission of the VCSEL is inhibited by plating the gold on the top, the intensity from the modulator is obtained by collecting the power through a multi-mode fiber. Figure 3 shows the emission spectrum from the modulator output, under the modulation at 0 V reverse bias. We carried out the small signal characteristics modulation. The output from the modulator is modulated by superimposing a RF signal at different reverse-bias voltages. The VCSEL is pumped by a fixed DC current of 8 mA. Output light is captured by a photo-detector (PD) with a bandwidth of over 30 GHz through a multi-mode fiber. The measured small signal response is shown in Fig. 4. We see two resonance peaks which may come from the beating of the neighboring sub-peaks shown in Fig.3. The small signal response of the fabricated device shows a large enhancement of 60 dB > in the modulation amplitude at frequencies beyond 35 GHz.

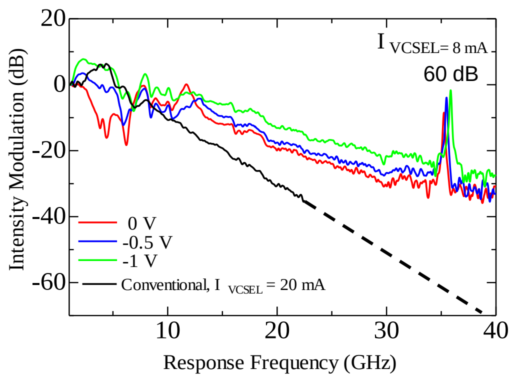


Fig. 4 Measured small-signal modulation response of the modulator integrated VCSEL with the different reverse bias voltages while VCSEL bias current is fixed at 8 mA.

CONCLUSION

In conclusion, we demonstrated a compact electro-absorption slow-light modulator laterally-integrated with an 850 nm VCSEL, which enables highly efficient millimeter-wave modulation. The small signal response of the fabricated device shows a large enhancement of over 60 dB in the modulation amplitude at frequencies beyond 35 GHz.

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