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60 GHz Harmonic Optoelectronic Up-Conversion Using an InAlAs/InGaAs Metamorphic High-Electron-Mobility Transistor on a GaAs Substrate

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This letter reports the demonstration of 60 GHz harmonic optoelectronic up-conversion using an InAlAs/InGaAs metamorphic high-electron-mobility transistor (HEMT) on a GaAs substrate. Using 10 GHz or 30 GHz local oscillator signals, we successfully up-convert optically transmitted 1 GHz signals into a 60 GHz band. After investigating the dependences of optoelectronic mixing efficiencies on the bias conditions of the HEMT, we determine the optimum bias conditions for maximizing harmonic optoelectronic up-conversion efficiency. [DOI: 10.1143/JJAP.42.L658]

KEYWORDS: metamorphic HEMT, photodetector, optoelectronic mixer, millimeter-wave, radio-on-fiber systems

Fiber-optic/millimeter-wave transmission systems have received much attention because they provide low loss, wide bandwidth and flexible transmission systems. Generally, several components such as a photodetector, electrical mixer, phase-locked oscillator and amplifier are required in the base station to perform the frequency up-conversion of optically transmitted data from the central office into desired millimeter-wave signals. This complex architecture for the base station remains as a serious obstacle for cost-effective construction of fiber-optic/millimeter-wave systems.[1)]

In order to overcome these problems, optoelectronic mixers have been intensively studied for the up-conversion of modulated lightwave signals to the desired millimeter-wave band with a local oscillator (LO).[2,3)] Among the various kinds of optoelectronic mixers, InP-based three-terminal devices including a high-electron-mobility transistor (HEMT) and heterojunction bipolar transistor (HBT) are promising candidates because they have high responsivity, high conversion gain and compatibility with a conventional monolithic microwave integrated circuit (MMIC) fabrication process. However, high cost and poor breakdown characteristics of InP substrates make it difficult to realize on-chip integration with other RF components including high-power amplifiers and the LO. In addition, the optoelectronic up-conversion schemes require a millimeter-wave phase-locked LO, which increases the cost of the base station.

In this letter, we propose a harmonic optoelectronic up-conversion scheme based on an InAlAs/InGaAs metamorphic HEMT on a GaAs substrate. The frequency up-conversion of 1 GHz optically transmitted signals to a 60 GHz band is successfully demonstrated with 10 GHz and 30 GHz LO signals. In addition, we investigate the dependences of mixing efficiencies on the bias conditions, which makes the optimization of harmonic optoelectronic up-conversion efficiency possible.

The InAlAs/InGaAs metamorphic HEMT of 0.25 μm gate length was fabricated with heteroepitaxial layers grown on a semi-insulating GaAs substrate by using molecular beam epitaxy. It consists of $In_xAl_{1-x}As$ graded buffer layer, 200 Å $In_{0.35}Ga_{0.65}As$/100 Å $In_{0.53}Ga_{0.47}As$ composite channel layers, $In_{0.35}Al_{0.65}As$ spacer layer, $5 \times 10^{12}\,cm^{-2}$ Si-delta doped layer, $In_{0.35}Al_{0.65}As$ barrier layer and $In_{0.53}Ga_{0.47}As$ capping layer from bottom to top. The important feature of this device is that it has a composite channel layer, which not only enhances carrier transport but also improves breakdown characteristics for high-power performance.[4)] In addition, the $In_{0.53}Ga_{0.47}As$ channel makes it possible for this metamorphic HEMT to detect 1.55 μm lightwave. The fabricated HEMT has a gate length of 0.25 μm and a threshold voltage of −1.1 V. The breakdown voltage and the maximum transconductance for the HEMT are −13 V and 680 mS/mm, respectively. Scattering parameter measurements show that current gain cutoff frequency and maximum oscillation frequency are approximately 95 GHz and 170 GHz, respectively.

Figure 1 shows the experimental setup for 60 GHz harmonic optoelectronic up-conversion. The lightwave from a laser diode directly modulated with 1 GHz was illuminated from the backside of the GaAs substrate using a single-mode lensed fiber. Since reflection and diffraction allow only partial coupling of incident lightwave into the device, EDFA was used for compensating the optical insertion loss. All measurements were performed in a common-source configuration by utilizing on-wafer 50 GHz RF probes. The gate port was connected to a frequency synthesizer providing LO signals and output signals from the drain port were measured with a spectrum analyzer, which can measure signals up to 26.5 GHz. For a 60 GHz up-conversion experiment, an external V-band harmonic mixer was used.

Figure 2 shows the spectrum of harmonic optoelectronic up-converted signals at the 60 GHz band when a 30 GHz LO is applied to the gate port and optical IF of 1 GHz is

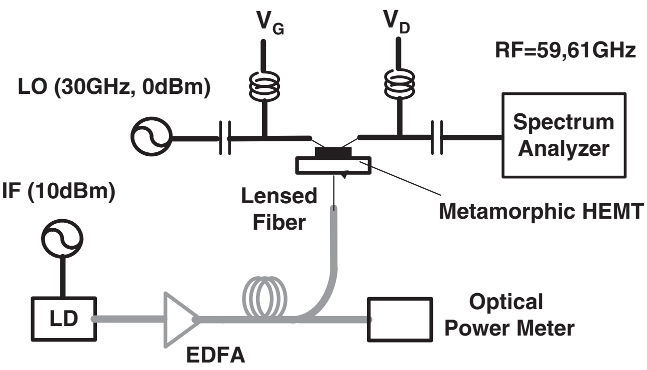

Fig. 1. Experimental setup for 60 GHz harmonic optoelectronic up-conversion.

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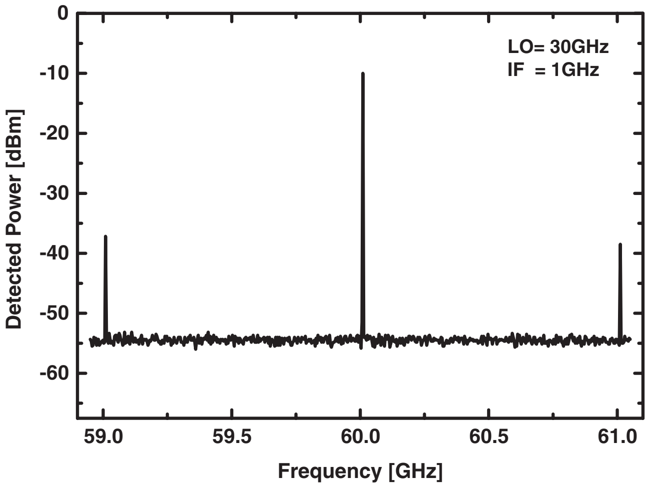

Fig. 2. Harmonic optoelectronic up-converted spectrum at the 60 GHz band under the conditions of 30 GHz LO with 0 dBm and bias of $V_G = -1.5$ V and $V_D = 0.5$ V.

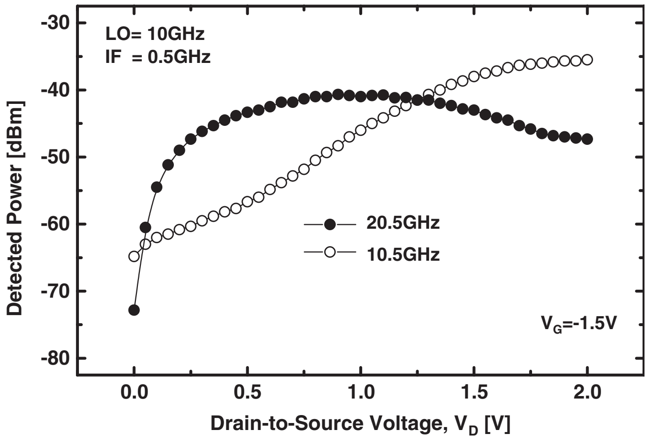

Fig. 4. Up-converted signal powers at $f_{LO} + f_{IF}$ and $2f_{LO} + f_{IF}$ as a function of V_D. 10 GHz LO with 0 dBm and the 500 MHz optical IF were used. —•— $2f_{LO} + f_{IF}$ (20.5 GHz) —○— $f_{LO} + f_{IF}$ (10.5 GHz)

illuminated. We clearly observe a stable 61 GHz up-converted signal with a power of −38.5 dBm. The bias conditions are $V_G = -1.5$ V and $V_D = 0.5$ V. When a 10 GHz LO was applied, the 61 GHz up-converted signal power was −45 dBm. For the measurement, two low-noise amplifiers were used to compensate severe loss due to RF cables and probes used in the measurement that were guaranteed for use below 50 GHz. The incident optical power measured at the end of the lensed fiber was 10 dBm. In our proposed scheme, the metamorphic HEMT performs 1.55 μm modulated lightwave photodetection and harmonic frequency up-conversion, simultaneously.

During the experiments, we found that the mixing efficiencies strongly depend on the gate and drain bias conditions. In order to optimize the bias conditions for maximizing harmonic optoelectronic up-conversion, experiments were performed in a 20 GHz band with the 10 GHz LO and 500 MHz IF, because the measurement sensitivity at 60 GHz is limited by the high background noise level of the external V-band harmonic mixer. Figure 3 shows the

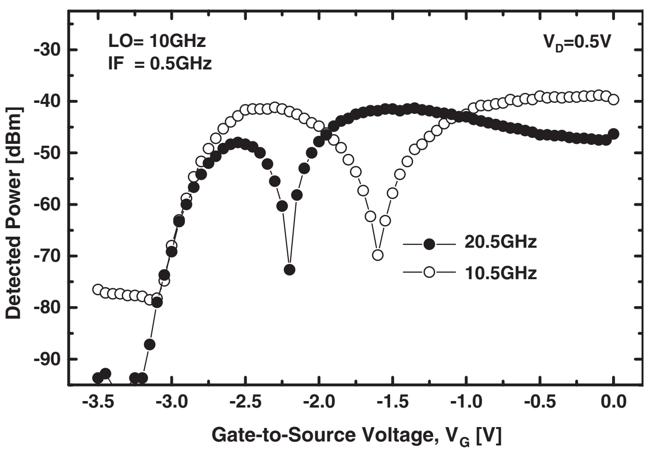

Fig. 3. Up-converted signal powers at $f_{LO} + f_{IF}$ and $2f_{LO} + f_{IF}$ as a function of V_G. 10 GHz LO with 0 dBm and 500 MHz optical IF were used. —•— $2f_{LO} + f_{IF}$ (20.5 GHz) —○— $f_{LO} + f_{IF}$ (10.5 GHz)

dependence of optoelectronic up-converted signals at $f_{LO} + f_{IF}$ and $2f_{LO} + f_{IF}$ on the gate bias. It is shown that the mixing efficiencies depend on the gate bias, which is related to the nonlinearity of the HEMT.[3] It should be noted that the harmonic mixing product at $2f_{LO} + f_{IF}$ can be selectively enhanced while suppressing the $f_{LO} + f_{IF}$ product with an optimum gate bias, for example, $V_G = -1.5$ V. This feature is very advantageous in the harmonic optoelectronic up-conversion where harmonic mixing products at $2f_{LO} + f_{IF}$ are needed. The dependence of mixing products on the drain bias is shown in Fig. 4. In the linear mode of the HEMT, the harmonic mixing product at $2f_{LO} + f_{IF}$ is enhanced. However, it decreases as the drain bias increases in the saturation mode. The mixing product at $f_{LO} + f_{IF}$ shows a different dependence. These results agree with the dependence of an electrical mixer in which harmonic mixing products become stronger in the linear mode of the HEMT.[5]

In conclusion, 60 GHz harmonic optoelectronic up-conversion using a single metamorphic HEMT is successfully demonstrated. By investigating the dependences of mixing efficiencies on bias conditions, it is shown that harmonic optoelectronic mixing components can be selectively enhanced while suppressing other mixing components. We believe such a metamorphic HEMT as well as other functional circuits based on it can find useful applications for realizing cost-effective base stations for fiber-optic/millimeter-wave transmission systems.

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