Characteristics of InP/InGaAs based Heterojunction Phototransistor for Optoelectronic Mixer

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Characteristics of InP/InGaAs based Heterojunction Phototransistor for Optoelectronic Mixer

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This certifies that the bachelor's thesis of Seung-Chan Han is approved.

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Abstract

Characteristics of InP/InGaAs based Heterojunction Phototransistor for Optoelectronic Mixer

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Wireless communication is becoming an crucial area of today's life. With chasing this trend, there are continuously growing demands for ultra-wideband transmission due to insufficiency of available frequency band and increase of information. To satisfy this, millimeter wave has drawn lots of technical attentions. In spite of its ability to transmit ultra wide bandwidth signals, available propagation range is restricted by its own nature. To overcome this limitation, Radio-on-Fiber technology is treated as one of effective ways.

Conceptually, RoF technology indicates that microwave signals are distributed by optical fiber into each remote up antenna units.

Among various RF devices to implement RoF system, optoelectronic mixer at each remote antenna unit plays a weighty role to convert input modulated optical signals into radio frequency signals. In this thesis, for applying InP/InGaAs heterojunction transistor as an optoelectronic mixer, I examined its possibility on experimentally manifold aspects including DC characteristics, optical AC characteristics and mixing characteristics.

Keyword : InP/InGaAs heterojunction phototransistor, optoelectronic mixer, radio-on-fiber technology, DC characteristics, optical AC characteristics, mixing characteristics

I. Introduction

As wireless communication is highly developed, demands for wider bandwidth and higher speed transmission are rapidly increasing. To achieve this, it is imperative to raise the carrier frequency into much higher frequency. Among various frequency bands, millimeter-wave band becomes technically and commercially expected to be utilized soon because of its own advantageous natures for ultra-wideband communication. Millimeter-wave is an electromagnetic wave having a frequency from thirty to three hundred GHz. This band has a wavelength of one to ten millimeters and following characteristics. With this band, ultra wide bandwidth over 1GHz can be implemented for wireless communication. Unfortunately, it can not propagate over few hundred meters in the air since this band experiences serious loss in the air. Due to such restriction, there are many antenna stations required for broadening its available propagation range and it causes raising costs to implement the system using this band. Thus, it is momentous to develop cost-effective and physically competitive system for millimeter wave communication [1].

Instead of construction of many base stations, it becomes an attractive solution to utilize optical fiber to link the central base station, which centralized expensive and distributed RF processings including local oscillator, with remote antenna units. This system is named as RoF(Radio-on-Fiber) technology, a technology by which microwave signals are distributed by means of optical components and techniques. By delivering the radio signals directly, the optical fiber link avoids the necessity to generate high frequency radio carriers at the antenna site and these sites are usually remote from easy access. Also, such signals experience very low attenuation through optical fiber. As known well, optical fiber has only 0.2dB loss for one kilometer at 1550nm wavelength [14]. Especially, in order to construct simpler antenna base, it is essential to implement efficient method to convert frequency down and up respect to the requirements [3]. Accordingly, optoelectronic mixer performing frequency conversion becomes crucial issue to achieve mentioned purpose. To achieve this goal, heterojunction phototransistors have been one of competitive candidates because of its own characteristics for optoelectronics mixer and abilities for integration and many elaborates have concentrated on verifying and improving its performance. To estimate the performance of heterojunction phototransistors, one needs to analyze its figure of merits including modulation response, conversion gain and distortion characteristics. It is the first to investigate them before applying heterojunction phototransistors to actual RoF systems. Figure 1.1 shows a fundamental scheme for the system with RoF technology.

In this thesis, fundamentals of InP based heterojunction phototransistor will be firstly described. Then, following chapters provide well-organized information about experimental environments for each measurement and result. Experimental elaborates are consisting of measuring device characteristics, optical AC characteristics and mixing characteristics in the case of 10GHz LO frequency. Especially, it encompasses optimized transistor bias conditions for better performance though observing bias dependencies.

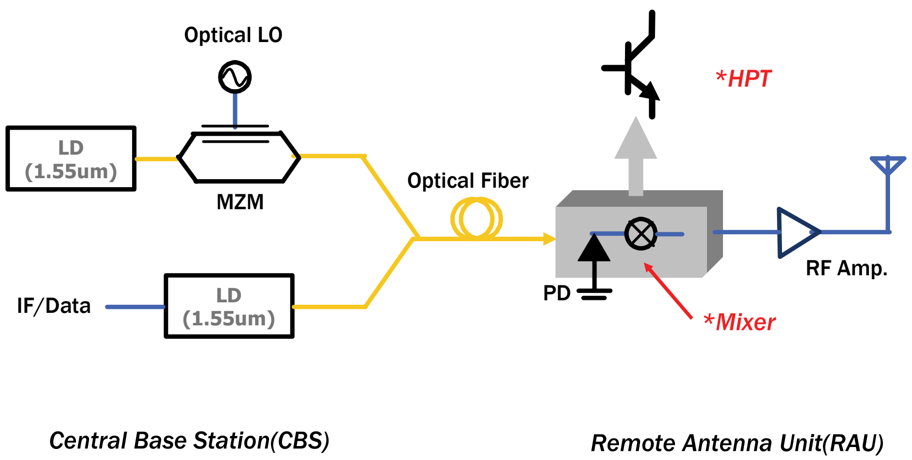


Figure 1.1 Conceptual scheme for remote up-conversion applied by radio-on-fiber technology

II. Background

A. Physics of InP-based heterojunction phototransistor

Indium-phospide (InP) heterojunction bipolar transistors(HBTs) are very suitable devices for millimeter-wave RoF systems due to its high optical responsivity and excellent high-frequency performance.

A heterojunction bipolar transistor consists of a heterojunction in the base-emitter junction and a homojunction in the base-collector junction [4]. Among them, HBTs with optical window on top of emitter for optical illumination are named as heterojunction photo-transistors (HPTs). Optical window makes the emitter efficiently absorb illuminated light.

The InP HPTs are fabricated with the lattice-matched layers epitaxially grown on a semi-insulating InP substrate by applying molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD) [5]. Materials lattice-matched to InP are $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$. Thus, InP HPT is the general designation for HPTs on InP substrates, and the terms InP/InGaAs and InAlAs/InGaAs describe the emitter-base heterostructure pairs of InP HPTs. Typically, the epitaxial layer of single-HPTs consists of p^+-doped

InGaAs base, n-doped InGaAs collector and n-doped InP emitter. The InGaAs base is intended to be thin and heavily doped to minimize the base transit time and the intrinsic base resistance. InP used for the collector has easier suppression of current blocking, less undesired conduction band offset and ghier electron saturation velocity than InAlAs. For the subcollector of InP HPTs, heavily doped InGaAs is usually applied since the subcollector preferred a low-field region and high electron regardless of the bandgap energy [6]. Above properties make it possible to achieve much higher speed of InP HBTs than that of silicon based HBTs.

Performance of HPT devices can be recognized by the discussion about following data including RF characteristics and noise figure. Conventional HPTs show extremely high frequency limits. InP HPTs have exceeding 300GHz for its cutoff or oscillation frequency from a recent report and such performances are higher than all other kinds of bipolar transistors [7], [8]. Such high-speed performance is a key reason why it is compatible to implement RoF system. In addition, InP HPTs are appropriate to detect widely used optical signal-1.55μm wavelength- since they have smaller bandgap energy than photon. On minimum noise figure aspect, InP HPTs have much superior performance, about 0.5 dB at 2GHz [9], than other HPT devices even though the output power gained from InP HPTs is lower than that from GaAs devices.

B. Information about InP/InGaAs HPT measured in this thesis

Following device structure shows the vertical structure of typical InP/InGaAs heterojunction phototransistor. The device used in this thesis was fabricated by ETRI and it had 2.0um×8.0um for its emitter size. Empirical top illumination responsivity was measured to be 0.05A/W.

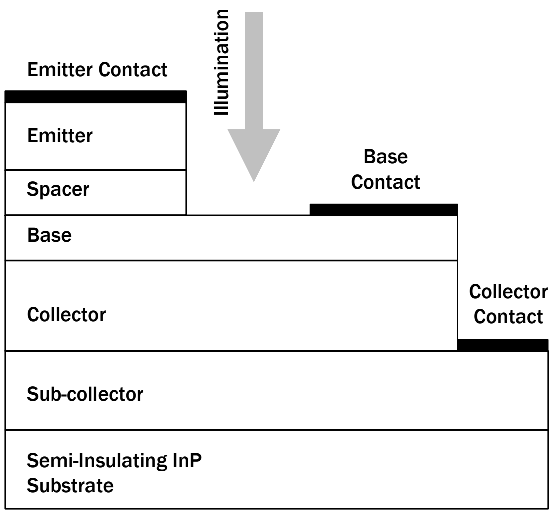


Figure 2.1 Vertical structure of typical InP/InGaAs HPT device

III. Experimental Results

A. Device characteristics

The basic experimental arrangement is depicted in Figure 3.1. DFB Laser diode generated 1550 nm optical signal, which had 15dBm optical power, directly modulated by 100MHz IF signal and it was illuminated onto the optical window on HPT through the lensed fiber. EDFA and optical attenuator were connected for controlling the optical power. With this experimental setup, its photodetection characteristics were extracted with semiconductor parameter extracter (HP4145B) and RF characteristics were detected by RF spectrum analyzer. Based on this arrangement, a part of them could be modified respect to what parameters required. Firstly, to measure DC characteristics without optical illumination, all components to illuminate onto the device was removed and measured by only semiconductor parameter analyzer. Those removed components were used to consider the illumination effect in section (A.2).

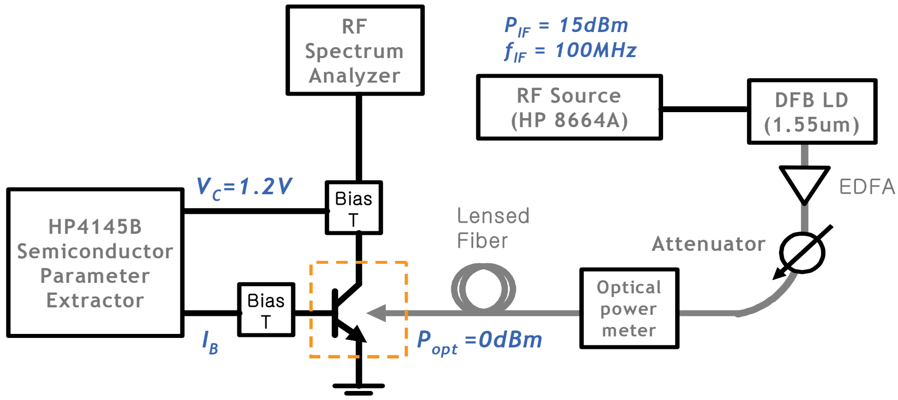
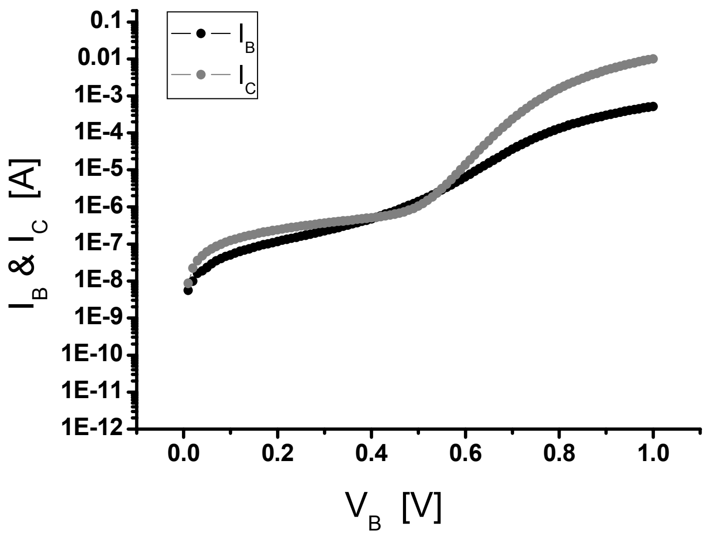


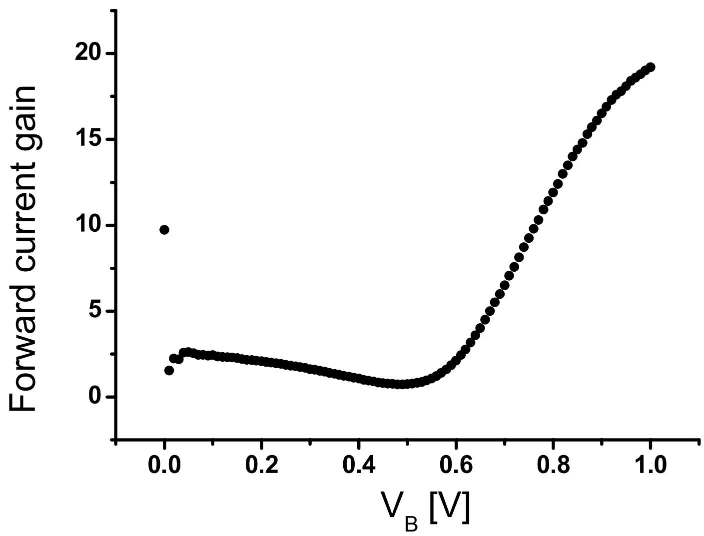
Figure 3.1 Experimental arrangement for device characteristics measurement

(A.1) DC Characteristics without optical illumination

In order to investigate DC characteristics of given HPT, gummel plot of the HPT and current gain property were described in Figure 3.2 by Semiconductor parameter extractor. Its gummel plot followed typically reported trend and Figure 3.2 (b) showed that this HPT had relatively low current gain, about 20 at 1.0V base voltage bias.



(a)



(b)

Figure 3.2 (a) Gummel Plot for InP/InGaAs HPT (measured in the dark)

(b) Extracted current gain for InP/InGaAs HPT (I_C over I_B)

(A-2) DC characteristics with optical illumination

Figure 3.3 shows measured collector-current (I_C) as a function of collector voltage (V_C) with 100µA base current step. It was observed that 100µA increase in I_C with 0dBm optical illumination as can be seen in the figure. This additional current was amplified virtual base current derived from photo-generated electron-hole pairs absorbing sufficient energy to overcome bandgap difference from illuminated light. As illustrated in Figure 3.4, collector current increased with increasing incident optical power onto the device from -3 to 6dBm with the step of 3dBm. From these results, optical responsivity could be calculated to be 0.05A/W.

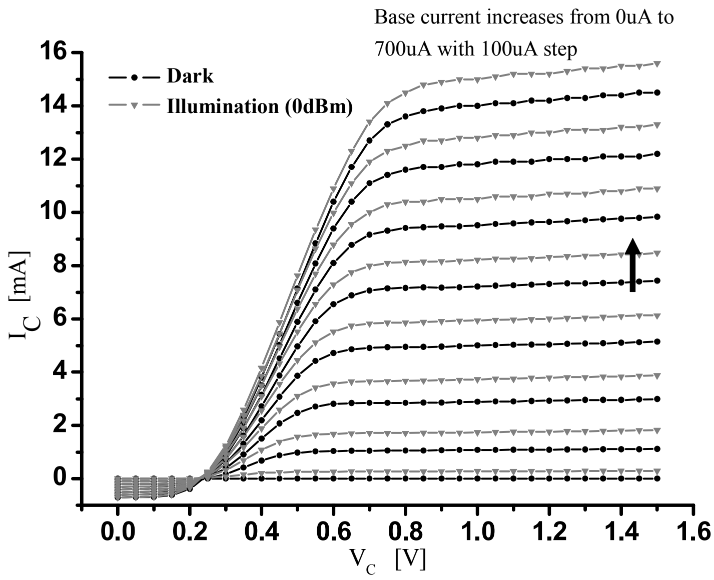


Figure 3.3 I_C versus V_C under dark and illuminated conditions

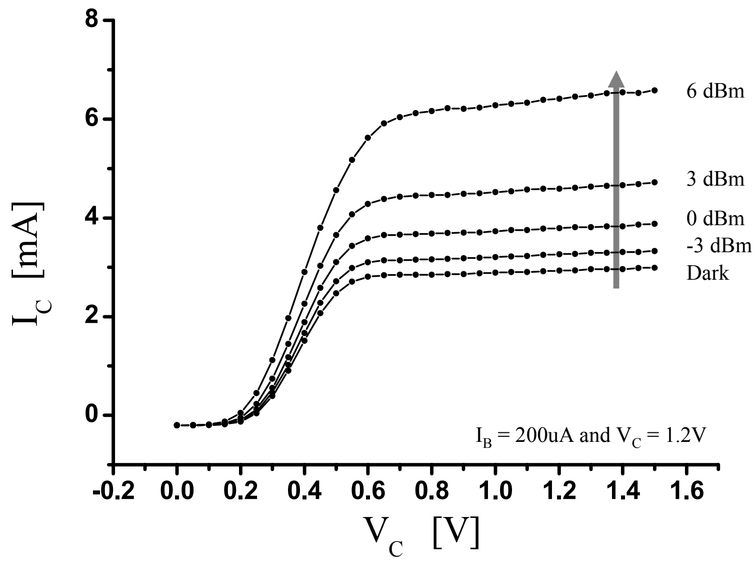


Figure 3.4 I_C change with increasing incident power with the step of 3dBm

B. Optical AC Characteristics

(B. 1) S-Parameter for the device

To investigate electrical AC characteristics of the device, experimental arrangement was modified with connecting one RF source to the base terminal and network analyzer to the collector terminal. After calibration, four different S-parameters were properly extracted. Figure 3.5 shows measured cutoff frequency and maximum oscillation frequency, which are important factors to show RF performance of devices, for given HPT. Though unknown peak, which required to examine experimental setup, was detected at around 6GHz in the h-parameter plot, [1]cut-off frequency (f_T) and maximum oscillation frequency (f_{MAX}) were experimentally demonstrated to be 60GHz, 122GHz respectively.

[1] Cut-off frequency is defined as the frequency beyond which no appreciable energy is transmitted. It may refer to either an upper or lower limit of a frequency band

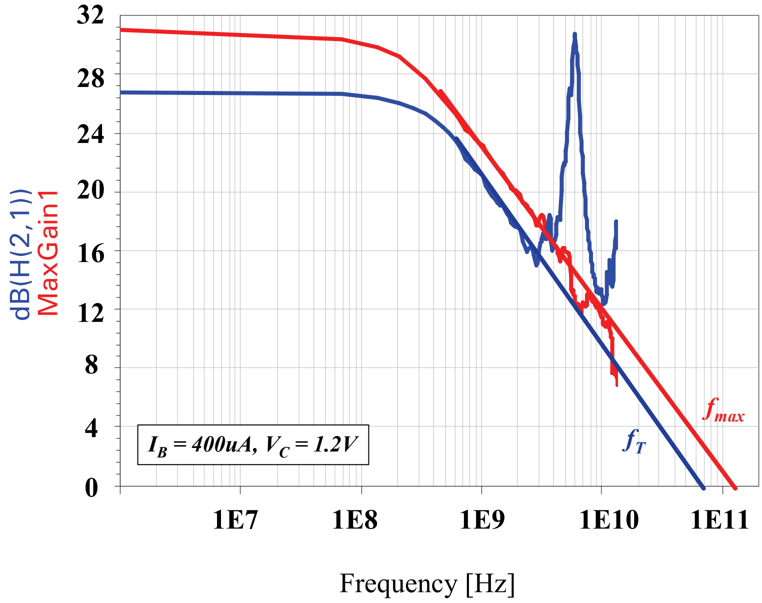


Figure 3.5 Frequency response of InP/InGaAs HPT under I_B = 400uA, V_C = 1.2V and 0dBm optical illumination

(B. 2) Optical Frequency Response

With fitting PD-mode (under no base voltage bias) to 0dBm, it was possible to observe phototransistor internal gain when the device operated as a transistor. Below figure shows that given device had around 24dBm for phototransistor internal gain when 400uA base current was applied.

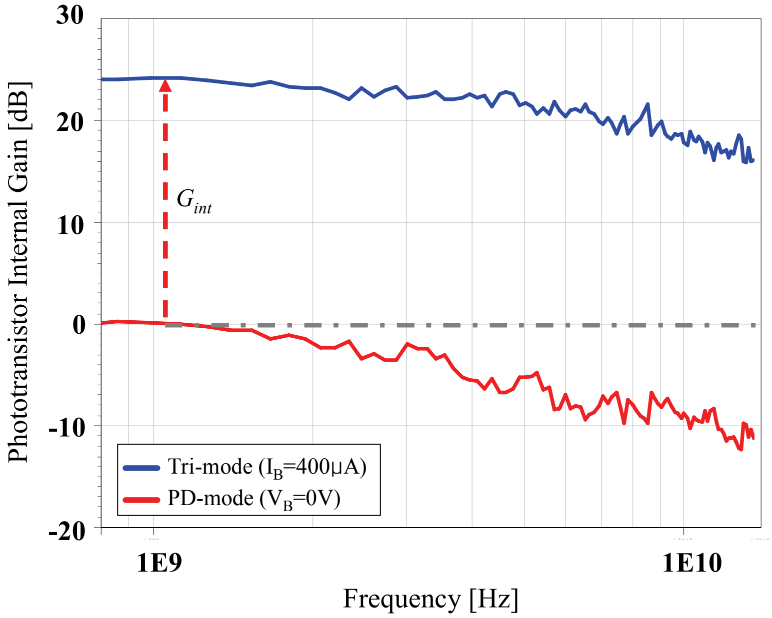
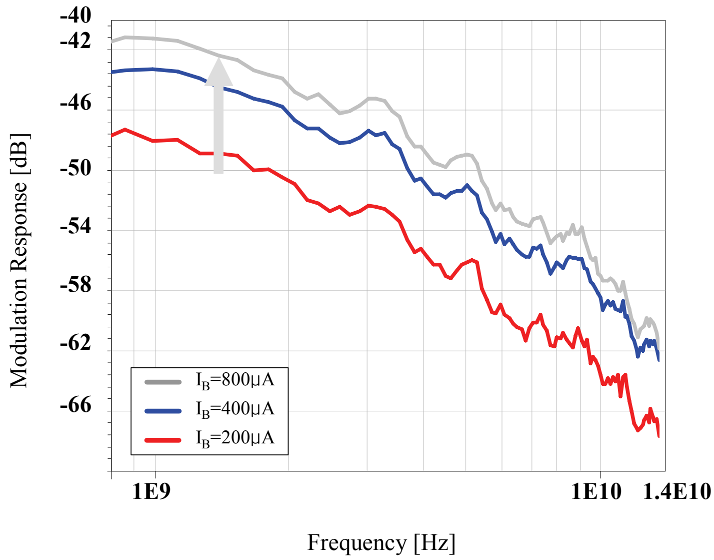
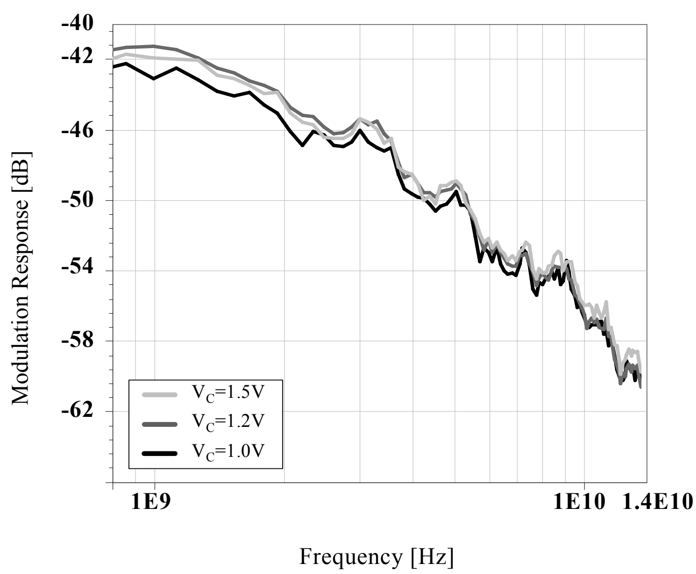


Figure 3.6 Measured phototransistor internal gain (G_{int}) of InP/InGaAs HPT It was measured for photodiode mode under zero base voltage bias and for phototransistor mode under 400uA base current bias.

In Figure 3.7, there observed the bias dependency of optical modulation response according to varying base voltage and collector voltage.



(a)



(b)

Figure 3.7 Bias dependency of optical modulation response (a) change with varying base current bias (b) change with varying collector voltage bias

As depicted in Figure 3.7 (a), increasing base current caused raising optical modulation response but the increasing tendency became quite less than half of previous increase according to double the base current. However, it was also observed that there was no clear bias dependency with collector bias voltage to optical modulation response. Thus, if higher modulation response is needed, it is effective to make its base current higher.

(B. 3) Bias dependence of photodetection characteristics

Similar to the nature of general transistors such as BJT and MOS, heterojunction bipolar transistor also possess the same nonlinear property. It has been possible to examine nonlinear characteristics such as collector current versus applied voltage in previous experiment. Particularly, such property tended to induce the degradation of mixing performance. In order to reduce performance alleviation, it is one of possible options to optimize HPT's bias condition. Following experiments were conducted for obtaining optimum bias condition. The power of injected IF signal was measured to be -45dBm when the HPT operated in the PD mode. Figure 3.9 includes the detected power of LO, up-converted signal LO+IF at 10.1GHz and its second harmonic signal a 20.1GHz respectively. Empirical setup for observing photodetection characteristics and mixing characteristics is as follows.

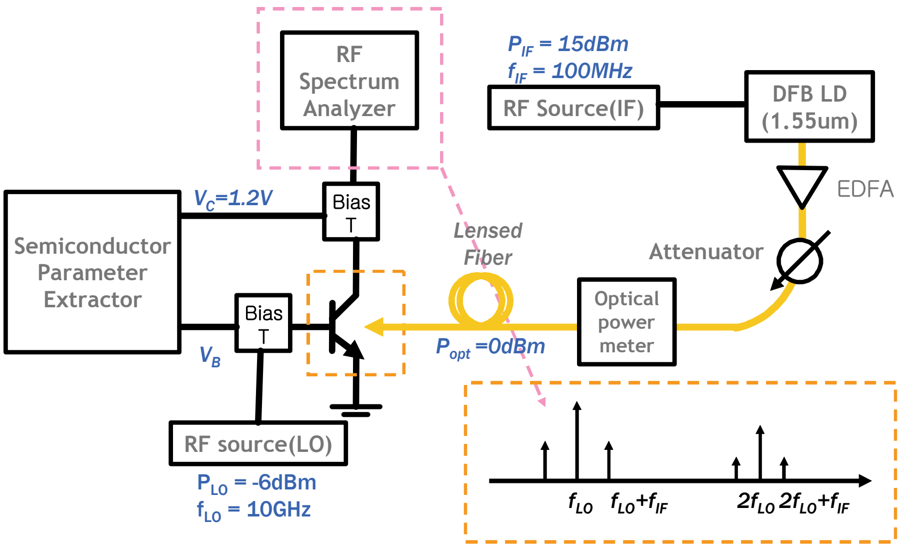


Figure 3.8 Experimental environment for measuring photodetection and mixing characteristics

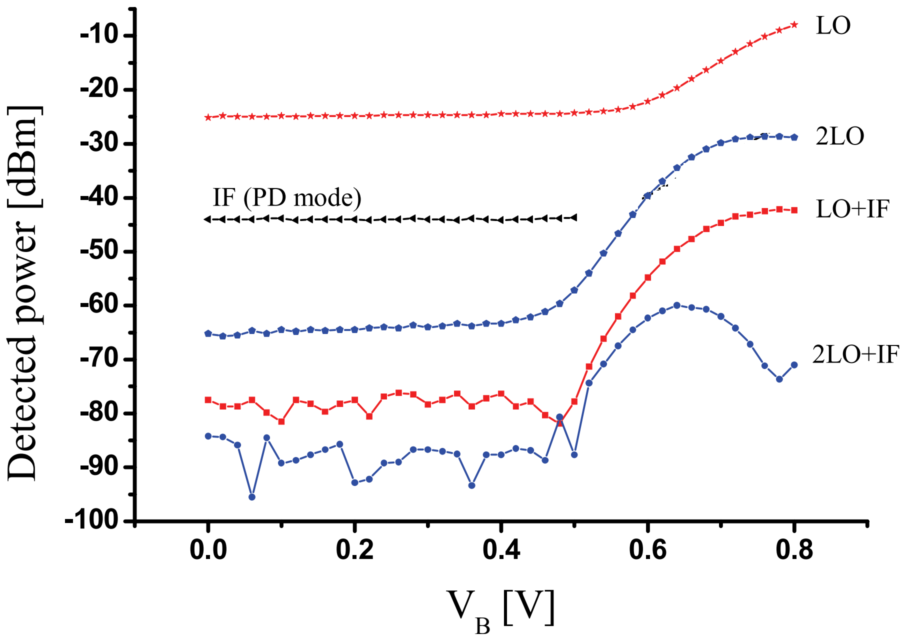


Figure 3.9 Detected power versus base voltage under 1.2V collector voltage

In Figure 3.9, the increase in detected power occurred after base voltage approached almost 0.5V, which was turn-on voltage for given device. It was also obtained that there was power gain due to the nature of HPT. Converted fundamental signal was detected at 10.1 GHz for up-conversion case and the second harmonic at 20.1 GHz. From the tendency of converted signals, it was possible to figure out that optimized bias point depends on which carrier frequency is needed. If the case required fundamental converted signal, biasing near 0.8V for base voltage was beneficial. Figure 3.10 shows a change in detected power with varying collector voltage 1.2V collector biased voltage. It seems meaningful for fundamental converted signal under referred base current condition.

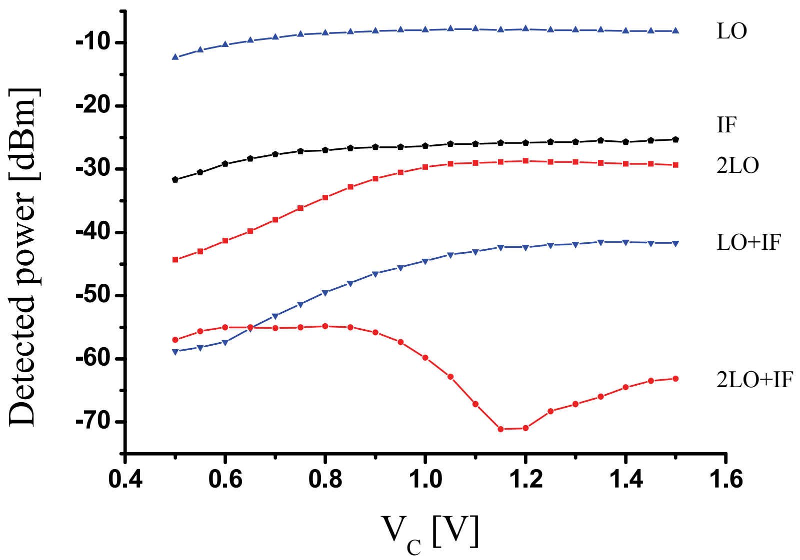


Figure 3.10 Detected power versus collector voltage under 200uA base current

C. Mixing Characteristics

(C. 1) Converted Spectrums

To convert input signals, 10GHz local oscillator (LO) signal having -6dBm power was connected and it was pumped into the base terminal by Anritsu 68177C RF generator. Following figures were obtained by RF spectrum analyzer under the condition with 200uA I_B, 1.2V V_C and -12dBm LO power. Both fundamental down and up converted signals were shown in Figure 3.11 and it is reasonable that the up converted signal had conversion gain of LO+IF dash line at 1.2V V_c bias voltage as depicted in Figure 3.11. Other signals shown around converted signals were spurious components derived from the nonlinearity of transistors. Successfully, the mixer generates output frequencies related to the combination of the addition and subtraction of LO and IF signals.

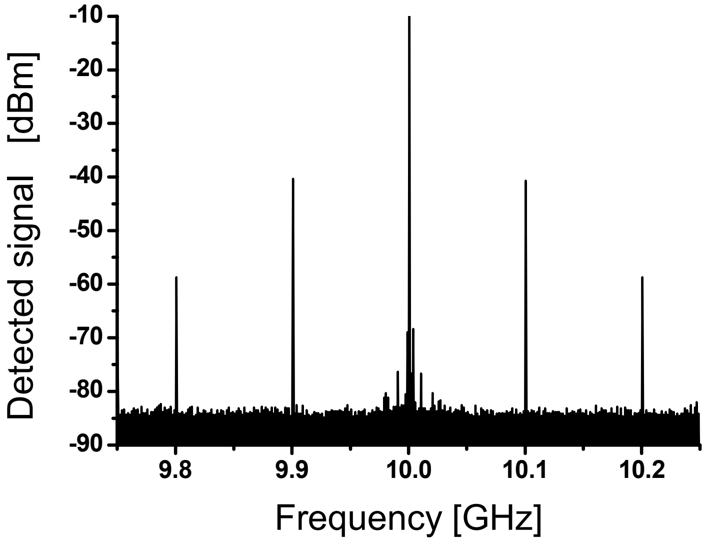


Figure 3.11 Spectrum of up and down converted fundamental signals detected at 10.1GHz and 9.9GHz

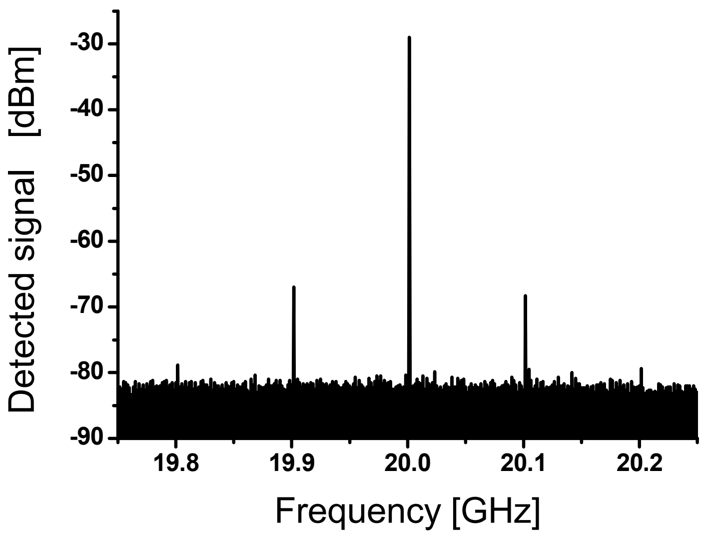


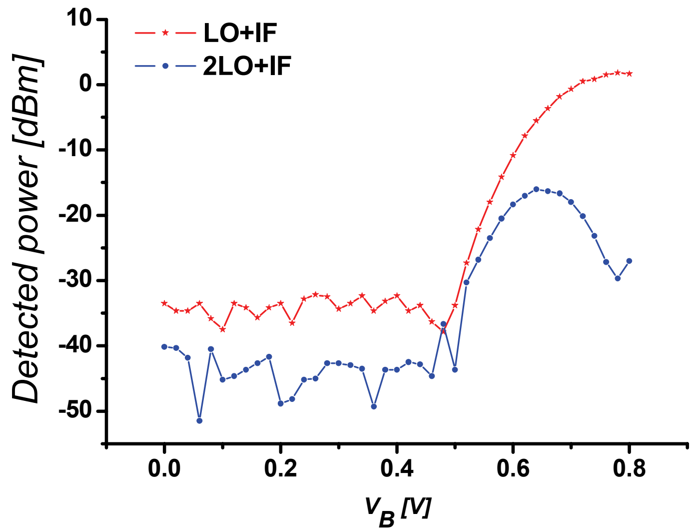
Figure 3.12 Spectrum of up and down converted second harmonic signals detected at 20.1GHz and 19.9GHz

(C. 2) Conversion gain

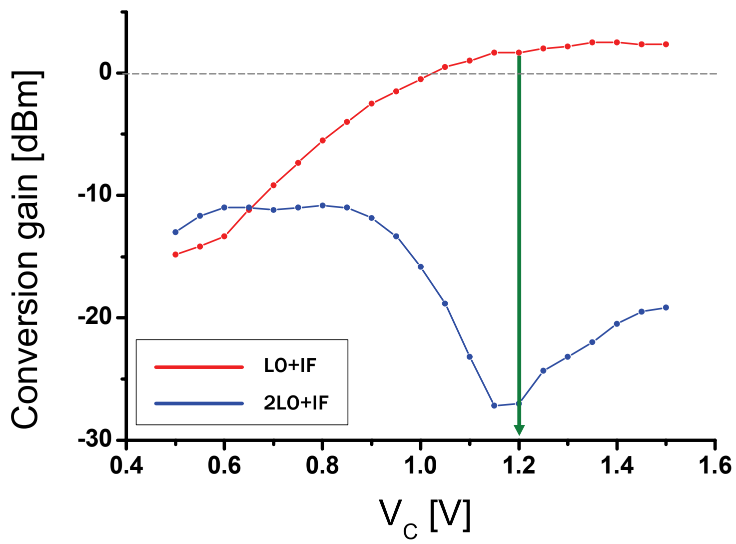
As observing detected signal spectrums, I could clarify conversion gain, which is one of important figure of merits representing mixing efficiency for optoelectronic mixers. Generally, conversion gain is defined as [3]

$$Conversion\ gain\ =\ \frac{Up-converted\ RF\ power}{Detected\ IF\ power\ at\ PD-\mathrm{mode}}$$

Estimated conversion gain for the HPT is as follows. Following figures show the effect of varying DC bias voltage when the LO level is 0dBm. Negative conversion gain means the loss of converted signals. In this figure, the conversion gain for the fundamental signal increased monotonically until around 3dBm with increasing collector voltage. Thus, conversion gain can be improved by applying appropriate DC bias to the HPT. Not only does this reduce the conversion loss and LO power requirements, it also offers an extra empirical adjustment for manufacturing variations [11]. From this fact, it is easily achieved to use 0.8V base voltage and 1.2V collector voltage biasing for using fundamental signals while the second harmonic signals are effectively suppressed under given LO power.



(a)



(b)

Figure 3.13 Up-conversion gain for given HPT as a function of (a) base voltage (V_C =1.2V) (b) collector voltage

(C. 3) SFDR according to bias dependencies

SFDR(Spurious Free Dynamic Range) indicates the dynamic range with suppressing the third-order intermodulation components to the noise level. As mentioned previously, the mixers have a large-signal LO which converts the intermodulation products to the IF frequency and to sidebands of all the LO harmonics and the level of the intermodulation products at the output of the mixer is given by

$$P_{IMn} = nP_1 - (n-1)IP_n$$

Where n is the order of the IM product, IP_n is the nth-order intercept point of the IM product [11]. It is noticed that IM product tends to be n times larger than fundamental signals. Due to such nature, to measure the tendency of IM products is important to determine available signal power range. Among various IM products, third order IM product is required to estimate the SFDR since third order IM products are the closest signals, which mostly affect on the available dynamic range, to the fundamental signals. To observe this parameter, there should be more than two frequency sources and laser diodes since two frequency signals simultaneously entering laser diode could arise another intermodulation not due to the nonlinearity of the transistor if only single laser diode was used to obtain the intermodulation spectrum. Thus, each frequency signal should be modulated individually and then the combined optical signal was illuminated into the HPT. Experimental setup for SFDR measurement is depicted in Figure 3.15.

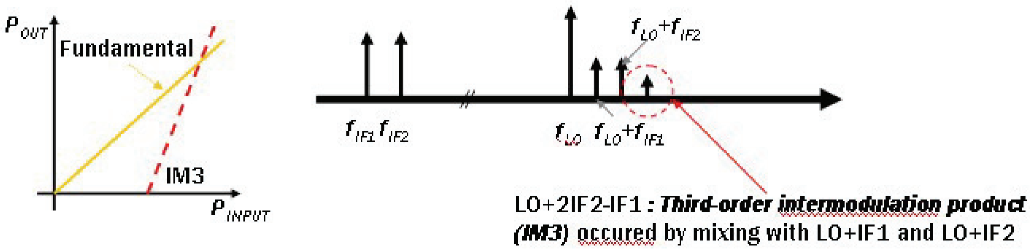


Figure 3.14 Tendency of increasing of fundamental and third intermodulation as a function of input power and their spectrums

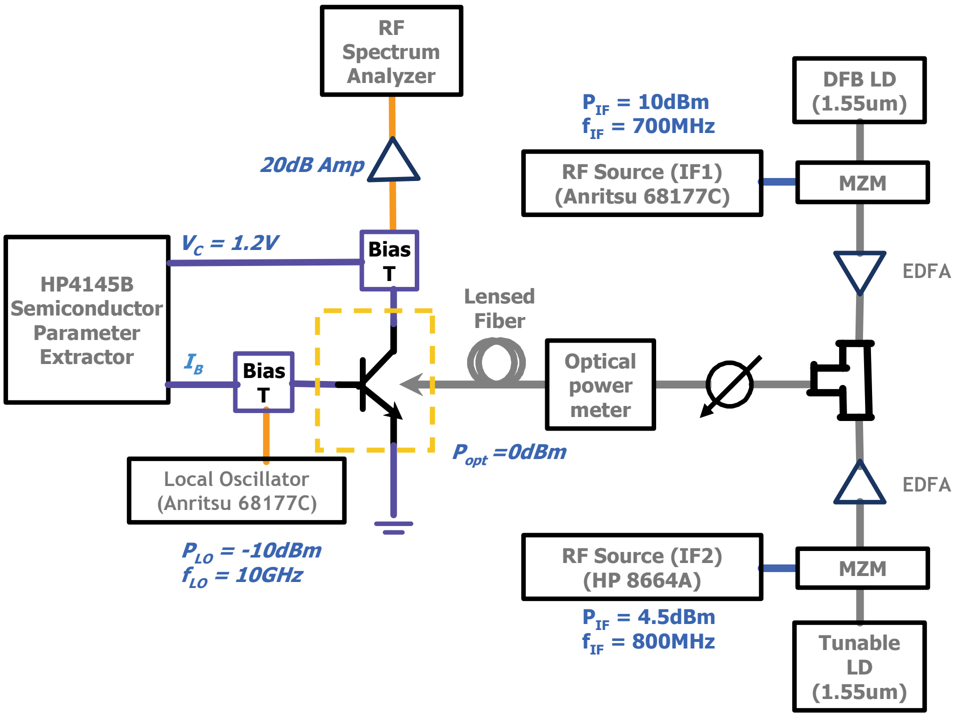


Figure 3.15 Experimental arrangement for SFDR measurement

Above described scheme is helpful to recognize two laser diodes with individual RF source were implemented for referred purpose. To modulate IF signal optically, two mach-zhender modulators which were available for 10GHz, 20GHz respectively were used with proper DC voltage bias. This approach ensures that the IM products were derived from not the optical source, but the transistor. On the basis of this scheme, 700MHz and 800MHz RF signals were successfully modulated. Because of different modulation efficiency of both modulators, the power of two RF signals should be different to have the same power value when they combined. The difference was estimated to be 5.5dBm higher for IF1 to satisfy the constraint. Incident optical signals were measured by spectrum analyzer with 20dB amplifier to observe the exact noise floor. Additional gain would be subtracted when plotting SFDR. Based on described information, measured SRDF is as follows.

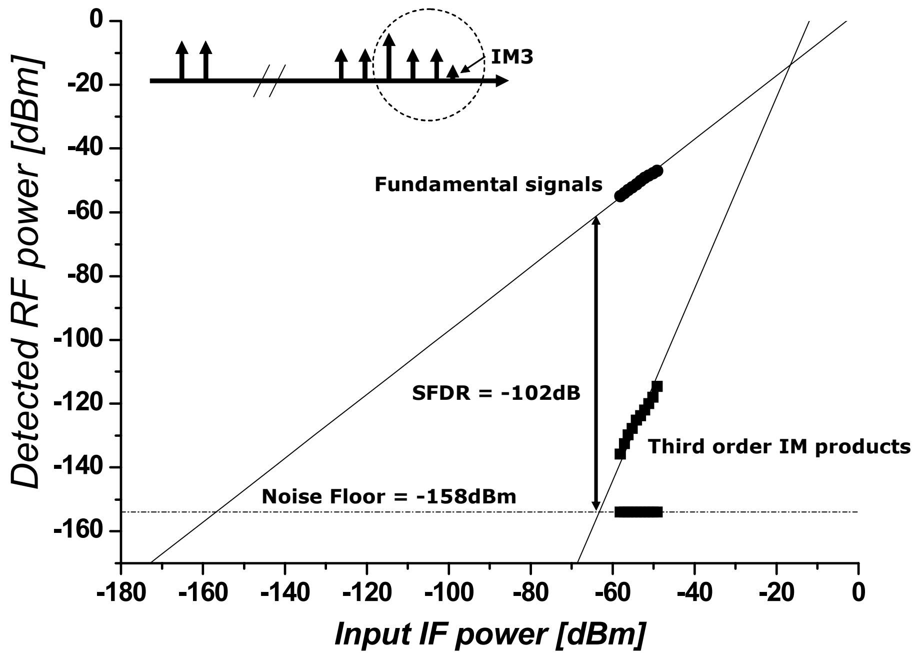


Figure 3.16 Detected RF power as a function of input IF power for SFDR measurement. LO = 10 GHz at -10dBm. HPT was biased with I_B = 400μA and V_C = 1.2V.

As depicted in Figure 3.16, third order IM products increased three times faster than the increase of fundamental signals. In addition, it was observed that available fundamental signal power was restricted under detected RF power -14dBm crossed fundamental signals with third-order IM product, named as IP3. The SFDR was measured to be 96 dB for the up-conversion when the noise floor was known as -158dBm. Its bias dependency is illustrated in Figure 3.17.

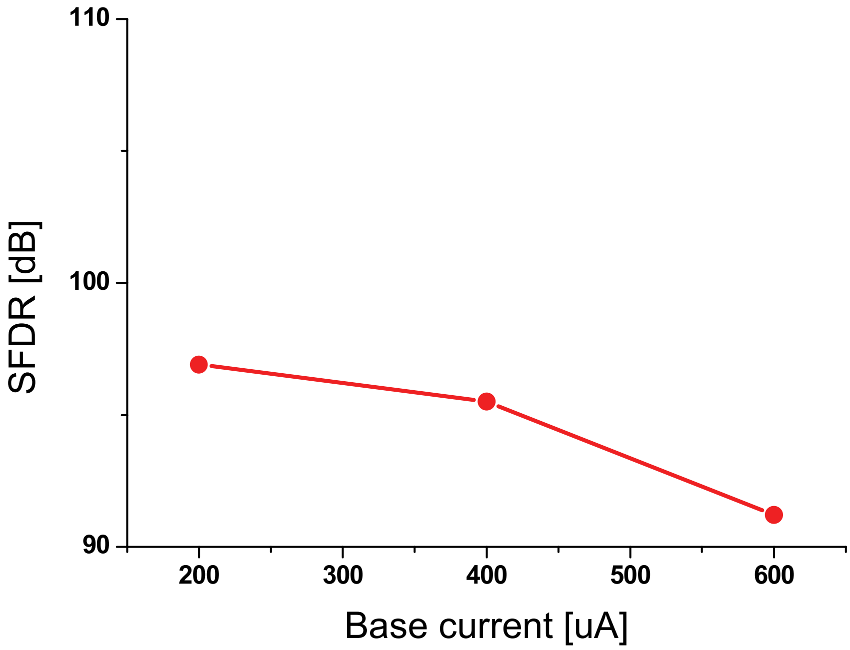


Figure 3.17 Bias dependency of SFDR measured under the same experimental environment as previous measurement

From Figure 3.17, increasing base current caused inferior SFDR though it made better conversion gain. Especially, the decrease between base current 400uA and 600uA was larger than decrease between base current 200uA and 400uA. Thus, proper base current bias is determined according to which specification is emphasized.

IV. Conclusion

Among various applications of InP/InGaAs HPT, in this thesis, I examined the possibility to utilize InP/InGaAs HPT as an optoelectronic mixer. Compared to other transistors, this HPT used in this thesis had less current gain, about 20 at 1.0V collector voltage. It notices that this device is hardly proper for general purposes of transistors. When modulated light having 1.55um wavelength and 0dBm optical power was illuminated onto the emitter of the HPT, optical responsivity was measured to be 0.05A/W, quite small value. From this result, though its quantum efficiency might be also small, I could observe the phenomenon that incident photons caused additional electron hole pair in the base.

Connecting network analyzer between laser diode and collector port, it was possible to extract its s-parameter, which is the important factor to show the RF performance of HPT. It was measured to be 60GHz for cut-off frequency and 122GHz for maximum oscillation frequency. Such high speed can not be achieved by conventional silicon bipolar transistor. Instead of inferior DC characteristics, its optical AC characteristics showed that it is appropriate device for RF processing.

In order to investigate mixing characteristics, 10GHz LO was applied to its base port and the result was detected by a spectrum analyzer. With this empirical arrangement, the spectrum analyzer detected both up and down converted signals. Also, it was possible to observe its second harmonic signals on both sides of 20GHz 2LO signal. About 3dBm conversion gain was measured at 1.2V collector voltage and this value is enough to utilize this device as an optoelectronic mixer. For measuring SFDR of the device, individually modulated two-tone lasers were used because intermodulation components could be derived from the optical source. As guaranteeing that intermodulation was merely occurred by two IF signals, SFDR was 96dB under 400uA base current and 1.2V collector voltage. Additionally, trade-off relation between conversion gain and SFDR was observed during varying base current bias.

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국문요약

광전 혼합기 구현을 위한
InP/InGaAs 이종접합 포토트랜지스터의 특성 분석

무선 통신이 오늘날 주된 통신 수단으로 인식됨에 따라 한정된 유효 주파수의 부족과 정보의 양의 증가로 인해 광대역 무선 전송에 대한 요구가 증대되고 있다. 이러한 수요를 충족시키기 위해 밀리미터파가 기술적인 측면에서 각광을 받고 있다. 그러나 밀리미터파가 광대역 신호 전송을 할 수 있음에도 불구하고 그 자체의 특성 때문에 전송 가능한 거리의 한계가 존재한다. 이를 극복하기 위해서 Radio-on-Fiber 기술이 효과적인 방안으로 제시되고 있다. Radio-on-Fiber 기술은 Base station에서 처리된 마이크로파 신호들을 광섬유를 이용해 각 원격 안테나단 까지 전송하는 기술을 총칭한다. RoF 시스템 구축을 위해서는 다양한 RF 소자들이 요구되지만, 그 중에서도 각 원격 안테나단에 존재하는 광전 혼합기는 광섬유를 통해 전송된 광신호에서 무선 통신으로 사용할 RF 신호로 바꾸는 매우 중요한 역할을 수행한다.

이에 본 논문에서는, InP/InGaAs 이종접합 포토트랜지스터를 광전

혼합기로 사용하기 위해 전기적 직류 특성, 광학적 교류 특성과 함께Mixing 특성을 분석함을 통해 해당 소자의 유용성을 검증하고자 한다.