Jurnal Teknologi
Full paper

Large Signal Model of Heterojunction Bipolar Transistor InP/InGaAs as an Optoelectronic Mixer

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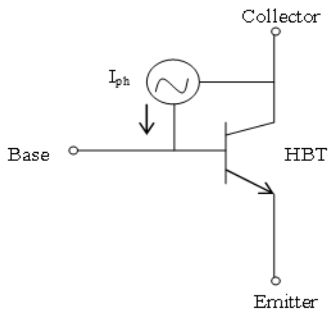
Article history

Received :23 October 2013
Received in revised form :
14 December 2013
Accepted :10 January 2014

Graphical abstract



Abstract

A large-signal model of InP/InGaAs single Heterojunction Bipolar Transistor (HBT) has been developed considering spectral performance and mixing. This model is based on Gummel Poon BJT model. HBT InP/InGaAs has been modeled and analyzed in this paper as an optoelectronic mixer (OEM). The HBT proposed was simulated by considering the wavelength of 1310 nm for an up-conversion frequency of 30 GHz. Its characteristics was further investigated to develop the appropriate structure device for OEM application. This proposed HBT InP/InGaAs can be potentially implemented in the broadband Radio over Fiber (RoF) system to perform photodetection and frequency up-conversion.

Keywords: Heterojunction bipolar transistor; optoelectronic mixer; InP/InGaAs

Abstrak

Model isyarat besar daripada InP/InGaAs Heterojunction Bipolar Transistor (HBT) telah dibangunkan dengan mempertimbangkan penilaian prestasi spektrum dan pencampur isyarat. Model ini berdasarkan kepada model Gummel Poon Bipolar Junction Transistor (BJT). HBT InP/InGaAs telah dimodelkan dan dianalisis dalam kertas ini sebagai pengadun optoelektronik (OEM). Model HBT yang dicadangkan telah disimulasi dengan mempertimbangkan panjang gelombang 1310 nm untuk frekuensi penukaran 30 GHz. Ciri-ciri yang didapati telah dianalisis untuk membangunkan peranti struktur yang sesuai untuk aplikasi OEM. HBT InP/InGaAs yang dicadangkan berpotensi dilaksanakan dalam sistem radio dalam gentian (RoF) jalur lebar untuk menjalankan fungsi pengesanan isyarat dan kekerapan penukaran isyarat.

Kata kunci: Heterojunction Bipolar Transistor; pengadun optoelektronik; InP/InGaAs

1.0 INTRODUCTION

Radio over fiber (RoF) system operating at millimeter-wave frequencies are offered for larger bandwidth, wider service coverage and larger channel capacity. Due to small coverage of millimeter-wave frequency RoF mm-wave, a lot of base stations required. Therefore, the base station must be simple and low cost. Base stations carried photodetector and mixer of frequency up conversion before distribute to end user. In order to simplify base station, optoelectronic mixer (OEM) was introduce for mixing local oscillator (LO) signal and intermediate frequency (IF) and upconverted to higher frequency up to several giga-hertz. HBT promising photodetector and optoelectronic converters for radio over fiber communication systems. In addition, HBT has identified as a suitable candidate of an OEM by simultaneously photodetecting an intensity modulated laser beam at 1.55 µm, frequency translating the detected signal to a higher or lower frequency which can provide high mixing efficiency up to 30 GHz. The single HBT perform photodetection and low noise frequency[1]. The use of HBT has attracted much interest among researchers[3-5].

Present researchers focus on integrated of detector and mixer in single devices. Many researchers aim to obtain simplification architecture with difference devices. CMOS Si Photodetector[7] is introduce to be operating at 60GHz. PIN PD operating at OEM in fast mode. However it has large thermal which associated with low resistance load at low input power[8]. Unitravelling Photodiode attracts researchers as an OEM in[11-12]. However this device have lack of internal gain.

HBT can be commonly found in modern ultrafast circuits, particularly the radio-frequency (RF) systems and other applications that require higher power efficiency such as power amplifiers in cellular phones. In addition, it is a natural choice for very high frequency military applications that demand high current drive, high voltage handling capability and low noise oscillating power. To be more specific, the InP/InGaAs HBTs have been used especially in optoelectronic circuits for 1300 nm to 1550 nm fiber optic communications. In such application, HBT proves to be a better choice than other devices such as HEMT and GaAs FETs[13] when implemented as an OEM. This is mainly because it can reduce phase noise after the optical injection matches with the injection of an optical signal which has been previously modulated at the oscillation frequency. In HBTs, there are two internal pn junctions where the mixing process occurs. The process happens when two junctions exhibit nonlinear exponential current-voltage characteristic.

As an optoelectronic mixer, the HBT non-linear gain characteristic can provide high mixing efficiency or the required conditions for oscillations[2]. In some cases, HBT were only two terminal devices (2T-HPT) with no electrical contact to the base[3] the base is then biased by the dc component of the optical input signal. Under such condition, the gain and the internal gain cut-off frequency (f_c) at low incident optical power are small. The optoelectronic mixing frequency-mixes the photocurrent signal in the photodetector with a local oscillator signal (LO) by using the inherent nonlinearlities in the device. Therefore HBT are suitable for three terminal photodetectors because the mixer requires a three port terminal for LO-, IF-, and RF-signals. In[15] presented the large signal and small signal analysis of HBT OEM for both down and up-conversion signal. The nonlinear nature of the current gain in an HBT makes it necessary to model the mixer under large signal conditions, and develop a small signal model to understand the physics behind the device operation.

This paper intends to report the large signal model characterization of HBT InP/InGaAs as an OEM. The HBT under study has been modeled and characterized to perform photo-detection for 1310 nm light-wave in the InGaAs base-collector region and frequency up-conversion to 30 GHz. Gummel poon is excellent portrayal of the circuit characteristics of HBT. HBT is design in large signal Gummel Poon model which develop based on conventional BJT. In this project, we develop the model of Gummel Poon model in Microwave Office (MWO) system simulation. The explanation of development are shown on next section.

■2.0 THEORY AND MODELING

An incident light is directed to the optical window of the HBT. In this work, the base and collector terminals are made of InGaAs, with optical light at 1310 nm wavelength. Due to the photon absorption of the light, electron-hole pair will be generated and occur in three regions, which are at the base, base-collection depletion and collector regions. They are immediately separated by the strong electric field. As a result, the primary photocurrent, I_{ph} begins to flow.

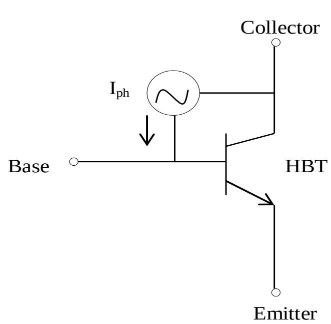


Figure 1 HBT equivalent circuit with voltage control source

In Figure 1, the photogenerated current is added between the internal base and collector access as the light penetrate through the junction base-collector. In optoelectronic mixing, the relation between the incident optical power and the photocurrent which generated into the base–collector junction, is linear. Thus, the model of optical detection through an internal photocurrent generator located between the base and collector[15].

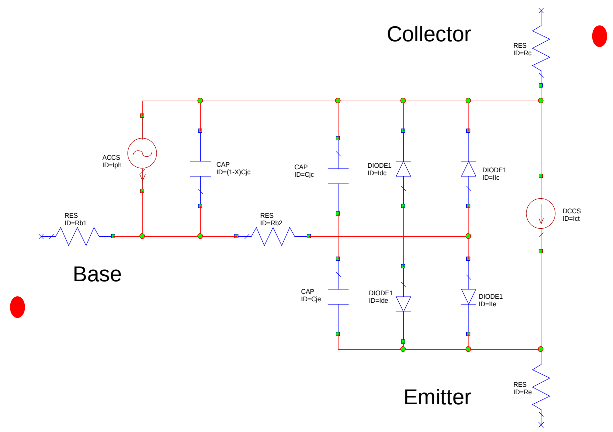


Figure 2 Circuit representation of Gummel-Poon large signal model HBT InP/InGaAs

In this large signal model, each of junction, base-collector, base-emitter are represent by ideal diode (I_{DE} and I_{DC}), a leakage diode (I_{LE} and I_{LC}) and capacitor, C_{jc} and C_{je}. In addition, diode is also present as a forward bias and reversed bias of HBT. β_R is the reversed current gain β_F is forward current gain. Figure 2 represents the extension of Gummel-Poon large signal model which is extension from BJT circuit model. The value of reversed current gain is small compare to forward current gain which usually large as the β_R present the doping concentration of collector. A current through diode flow as below:

i) For ideal diode

$$C_{je} = \frac{C_{be0}}{\left(1 - \frac{V_{BE}}{V_{BE0}}\right)^{MBE}} \quad (1)$$

and

$$I_{DC} = \frac{I_{sr}}{\beta_{fr}}\left[\exp\left(\frac{qV_{BC}}{n_c kT}\right) - 1\right] \quad (2)$$

Where by n_e and n_c in (1) and (2) is ideally factor of diode and I_{sf} and I_{sr} is saturated forward and reversed current.

ii) For non ideal diode

$$I_{LE} = C_2 I_{sf}\left[\exp\left(\frac{qV_{BE}}{n_{le} kT}\right) - 1\right] \quad (3)$$

and

$$I_{LC} = C_4 I_{sr}\left[\exp\left(\frac{qV_{BC}}{n_{lc} kT}\right) - 1\right] \quad (4)$$

Which C_2 and C_4 are weighing saturation currents. Current collector which injection electron from emitter to collector providing transistor electric gain. The value of I_{CT} is given as below:

$$I_{CT} = \left(I_{DE}.\beta_r\right) - \left(I_{DC}.\beta_f\right) \quad (5)$$

Capacitive components such as base-collector and base-emitter depletion capacitance is expressed as;

$$C_J = \frac{C_{j0}}{\left(1-\frac{V}{V_0}\right)^M} \tag{6}$$

which V is voltage across junction, C_{j0} is capacitance null voltage, V_0 is build on potential and M is junction profile-depend coefficient. Based on equation (6), C_{je} and C_{jc} can represent as eq. (7) and (8):

$$C_{je} = \frac{C_{be0}}{\left(1-\frac{V_{BE}}{V_{BE0}}\right)^{M_{BE}}} \tag{7}$$

and

$$C_{jc} = \frac{C_{bc0}}{\left(1-\frac{V_{BC}}{V_{BC0}}\right)^{M_{BC}}} \tag{8}$$

Due to distributed effects of base resistance, which the value of R_B is large, base collector capacitance is split between $X.C_{jc}$ and (1-X). C_{jc} which X is distribute coefficient of base-collector capacitance.

Current generator is connected in parallel of base-collector capacitance junction to take account of breakdown characteristics.

$$I_{BK} = I_C.B_F\left[\exp\left(\frac{V_{CB}-I_d.R_{br}+C_M.I_C.R_{br}}{N_{br}.V_T}\right)\right] \tag{9}$$

Which β_F, R_{br}, C_M and N_{br} are empirical parameters which best fits for IV characteristics. The parameters of indicate each parameters are shown as Table 1.

Table 1 Parameters for Gummel Poon HBT model

Parameters	Values
R_{EE}, emitter resistance	5Ω
R_{CC}, collector resistance	1 Ω
R_B, base resistance	10 Ω
n_e, forward ideally factor	1.1
n_c, reversed ideally factor	1.2
I_{DE}, ideal diode emitter	2.81mA
I_{DC}, ideal diode collector	183.93fA
C_{je}, junction capacitor at emitter	133.4fF
C_{jc}, junction capacitor at emitter	91.7fF
β_F, forward current gain	69
B_R, reversed current gain	0.07
I_{sf}, saturated forward current	0.002pA
I_{sr}, saturated reversed current	0.0035pA
V_Φ, build in potential	0.835V
X, distribution coefficient base-collector capacitance	0.05
C_2, coefficient emitter leakage diode	5
C_4, coefficient collector leakage diode	6000
M, transition capacitance coefficient	0.42
α, optical responsivity	0.4
I_{cs}, leakage current	6nA

3.0 RESULTS AND DISCUSSION

The mixer circuit was analyzed using the harmonic balance technique. A mixing model was carried out taking advantages of the nonlinearities of the HBT to achieve up-conversion of a modulated optical signal. The intensity of the optical signal was modulated by an IF signal ranging from 0.1 GHz to 1.3 GHz. As in Figure 3, the modulated optical input power was -10 dBm and the LO frequency injected into the base terminal was 30 GHz with an input power of -20 dBm to 0 dBm.

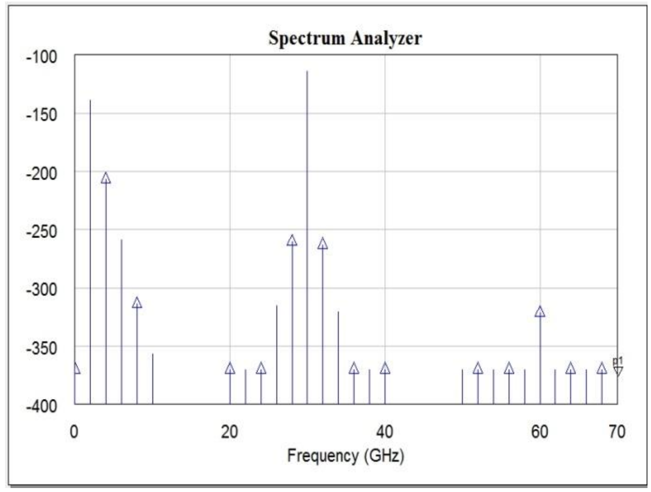


Figure 3 Output spectrum simulation of IF, LO and RF upconverted signals

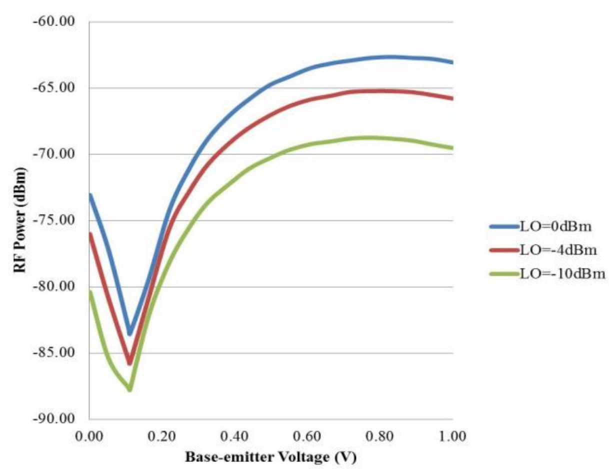


Figure 4 Simulated f_{RF}=30.4 GHz power as a function of base-emitter voltage with V_{CE} = 1.6 V

As demonstrated in Figure 4, the simulated RF power is plotted as a function of V_{BE} for three different LO power level with V_{CE} = 1.6 V. The mixing efficiency exhibited a maximum at V_{BE} = 0.86 V. The output power at the optimum V_{BE} for larger LO power was -63 dBm and for the lowest LO powers was -87 dBm. The main nonlinear effect in this bias range is the voltage dependence of the dynamic emitter resistance, R_{EE}, which determined the current gain of the HBT at high frequency.

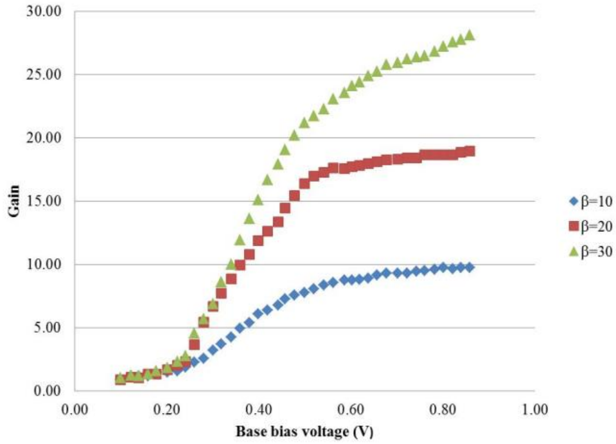


Figure 5 Photocurrent gain for a base bias voltage HBT for β = 10, 20 and 30

The main nonlinear effects in the HBT OEM were the voltage dependence of the dynamic emitter resistance and the variation of the current gain in the saturation regime [14]. As demonstrated in Figure 5, the maximum value achieve for gain in saturation region is 30. In the voltage-biased device, however, the base resistance, which is inversely proportional to the base width, is a source of thermal noise and also affects the biasing of the HBT.

■4.0 CONCLUSION

We have reported performance and characterization of physical model HBT InP/InGaAs as an OEM. In conclusions, we have reported on the simulation of a three-terminal HBT OEM at local oscillation frequency of 30 GHz. The operation frequency for this HBT have strong non linearity and enable to obtain high mixing frequency. Therefore, this device can be implemented as an optoelectronic mixer in millimeter-wave radio over fiber as it simplify the circuit with performance as frequency up-converted and photodetector in a single device.

Acknowledgement

This work was supported by Ministry of Higher Education Malaysia and the administration of Universiti Teknologi Malaysia (UTM) for the project financial support through Institutional Grant vote number 04H35. The authors acknowledge the Universiti Teknologi Mara (UiTM) for the financial support through SLAB funding to the first author.

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