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Research Article

Novel Analysis on the Optoelectronic Amplification Function for Photon Transport Transistor Circuit Using AC-based F Parameter

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ABSTRACT

The new concept of Photon Transport Transistor (PTT) as an optoelectronic amplification device has been proposed by the researcher at IBM Research Laboratory in 1989, as an alternative to Bipolar Junction Transistor (BJT). The PTT is composed by the opto-coupling of light emitting device and light receiving one. In this paper, we analyze the amplification function of PTT from the viewpoint of electronic equivalent circuit. For this purpose, we newly derive the AC (Alternating Current) based F parameter of the PTT emitter common circuit with fixed bias for AC small signal amplifier, using the VI characteristic equations of light emitting diode (LED) and photo diode (PD). Also, we discuss the amplification degrees of current, voltage, and power in the amplifier, using the derived parameter.

1. Introduction

In 1989, B. J. Van Zeghbroeck et al. at IBM Research Laboratory proposed the notion of Photon Transport Transistor (PTT) as an invention of optoelectronic device [1]. The PTT consists of the optical coupling between the light emitting device such as LED or Laser Diode and light receiving device such as Photo Diode (PD), where the carrier of the base layer is light (Photon) only. At the same time, the IBM researchers revealed the experimental results that the current gain and gain-bandwidth product was maximum 4 times and 70 MHz, respectively [1].

Moreover, later in 1996, W.N. Cheung and Paul J. Edwards have theoretically shown that the PTT in a positive feedback circuit becomes a very low-noise transistor, based on the numerical computation of noise figure [2].

After that, using the different style of PTT circuit from those of PTT described in the literature [1] and [2], it was reported that not only some prototype applications such as an audio amplifier, but also PTT circuit that works like a kind of thyristor were developed ([3], [4], [5]). The PTT used for applications is composed by the optical coupling of high-brightness LED and high sensitivity PD ([6], [7], [8]), and the style of applied PTT circuit is corresponding to that of emitter common circuit of conventional Bipolar Junction Transistor (BJT) ([9], [10], [11], [12]).

On the other hand, for the applied PTT emitter common circuit, the authors have investigated the DC (Direct Current) current amplification function of the PTT circuit. Thus, as an experimental result, we have obtained the DC current amplification factor hFE = 999 by PTT with positive feedback circuit ([13], [14]).

In this paper, for the analysis of the amplification function of PTT circuit for small Alternating Current (AC) signal, we newly derive the AC-based **F** parameter of PTT emitter common circuit with fixed bias, where the parameter stands for the components of **F** Matrix that represents the relation between the input voltage/current and output voltage/current of AC signal of the circuit.

2. BJT and PTT in Emitter Common Circuit
2.1. BJT Amplifier and h Parameters

The example of BJT emitter common circuit for AC signal amplification is illustrated in Fig. 1. This kind of BJT circuit is used for both of current and voltage amplification. Note that we denote the DC component of the variable as the variable with overlined.

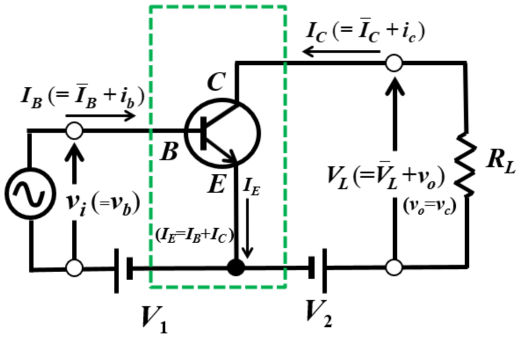


Fig. 1. BJT emitter common circuit where (***i**$_b$*, ***i**$_c$*, ***v**$_o$*) and $(\bar{I}_C, \bar{I}_B, \bar{V}_L)$ are AC components caused by AC signal ***v**$_i$* and DC ones in (I_C, I_B, V_L), respectively.

Especially, for the BJT emitter common circuit of small AC signal amplification, the equivalent circuit including a set of *h* parameters $\{h_{ie}, h_{re}, h_{fe}, h_{oe}\}$ is generally used as shown in Fig. 2 ([9], [10], [11], [12]).
Moreover, the equivalent relation equations of the circuit with *h* parameters in Fig. 2 (a) are as follows.

$$\begin{bmatrix} v_b \\ i_c \end{bmatrix} = \begin{bmatrix} h_{ie}i_b + h_{re}v_c \\ h_{fe}i_b + h_{oe}v_c \end{bmatrix} = \begin{bmatrix} h_{ie}, & h_{re} \\ h_{fe}, & h_{oe} \end{bmatrix} \cdot \begin{bmatrix} i_b \\ v_c \end{bmatrix} \tag{1}$$

These *h* parameters are obtained from the total differential equation for V_{BE} and I_C, assuming that they are the functions with variables I_B and V_{CE} such that $V_{BE} = f_1(I_B, V_{CE})$, $I_C = f_2(I_B, V_{CE})$, where $\overline{V_{BE}} = f_1(\overline{I_B}, \overline{V_{CE}})$, $\overline{I_C} = f_2(\overline{I_B}, \overline{V_{CE}})$ for DC components $\overline{V_{BE}}, \overline{I_C}, \overline{I_B}, \overline{V_{CE}}$.

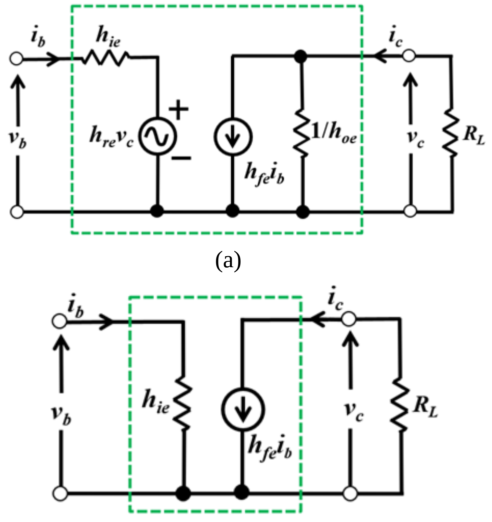


Fig. 2. Equivalent circuit using h parameters of BJT emitter common circuit for small signal amplification. (a) Precise equivalent circuit. (b) Simplified equivalent circuit when $h_{re} \approx 0$, $h_{oe} \approx 0$.

Then, corresponding to Eq. (1), we have the following Eq. (2).

$$\begin{cases} \Delta V_{BE}(\equiv v_b) = \left(\dfrac{\partial V_{BE}}{\partial I_B}\right)\Delta I_B + \left(\dfrac{\partial V_{BE}}{\partial V_{CE}}\right)\Delta V_{CE} \\ \qquad = h_{ie}i_b + h_{re}v_c \\ \Delta I_C(\equiv i_c) = \left(\dfrac{\partial I_C}{\partial I_B}\right)\Delta I_B + \left(\dfrac{\partial I_C}{\partial V_{CE}}\right)\Delta V_{CE} \\ \qquad = h_{fe}i_b + h_{oe}v_c \end{cases} \tag{2}$$

2.2. PTT Circuit and VI Equations of PD and LED

The PTT emitter common circuit with fixed bias is shown in Fig. 3.

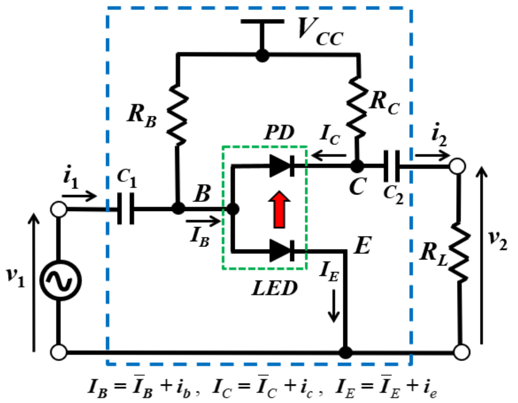


Fig. 3. PTT emitter common circuit with fixed bias for small signal amplification.

As for the practical PTT in Fig. 3, we are using the combination of four LEDs connected in series and one PD as shown in Fig. 4. The model numbers of LED and PD are shown below ([6], [7]).

LED: OSRAM LH CPDP-2T3T-1-0
(InGaAlP system, 3.1×3.1mm surface mount type)
PD: Hamamatsu Photonics S5107
(Si system, 14.5 x 16.5 mm surface mount type)

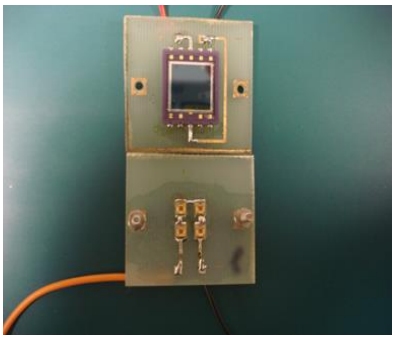


Fig. 4. Example of a practical PTT where the set of four LEDs connected in series and one PD are to be used facing each other at a certain distance (LED part: lower, PD part: upper) ([13], [14]).

The VI characteristic equations of PD and LED are shown in Eq. (3) and Eq. (4), respectively ([13], [14]). The meaning of symbol and the value are shown in Table 1 and Table 2, respectively.

$$I_C = \gamma^* I_E - I_{C0}\left(\exp\left(c_{PD}V_{BC}\right)-1\right),\ \ c_{PD} = \frac{q}{m_2 kT_{PD}} \tag{3}$$

$$I_E = I_{E0}\left(\exp\left(c_{LED}V_{BE}\right)-1\right),\ \ c_{LED} = \frac{q}{m_1 kT_{LED}} \tag{4}$$

Table 1. The symbol list of PTT characteristic formula.

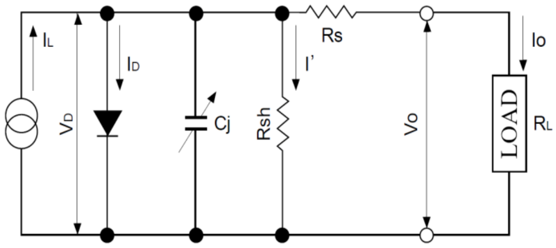
I_{E0}	Reverse saturation current in Emitter (LED)	I_{C0}	Reverse saturation current in Collector (PD)
m_1	Ideality factor (LED)	m_2	Ideality factor (PD)
q	Charge	k	Boltzmann's constant
T_{LED}	Absolute temperature of LED	T_{PD}	Absolute temperature of PD
V_{BE}	Base-Emitter voltage	V_{BC}	Base-Collector voltage
γ^*	Proportional constant	---	----

Table 2. The tentative constants of the formula.

I_{E0}	1.00×10^{-14} [A]	I_{C0}	1.00×10^{-14} [A]
m_1	3	m_2	3
T_{LED}	300 [K]	T_{PD}	300 [K]
q	1.602×10^{-19} [C]	k	1.380649×10^{-23} [J/K]

The Eq. (3) is an approximated VI characteristic equation of PD, based on the Eq. (5) from the PD equivalent circuit in Fig. 5 that are presented by the manufacturer ([7], [8]).

$$\begin{cases} I_O = I_L - I_S\left(\exp\dfrac{qV_D}{kT}-1\right) - I' \\ V_D = V_{BC} - I_O R_S \\ I' = \dfrac{V_{BC}-I_O R_S}{R_{sh}} \end{cases} \tag{5}$$



I_L : Generated current by incident light,
I_D : Current of diode, Cj : Junction capacitance,
Rsh : Shunt resistance, R_S : Series resistance,
I' : Current of Rsh, V_D : Voltage of diode,
I_O : Output current, V_O : Output voltage.

Fig. 5. Equivalent circuit of PD in the PTT circuit as shown in Fig. 3, where the upper part and the lower part correspond to the Base side and the Collector side, respectively, and Vo equals to V_{BC}.

The internal resistance Rs as described in Eq. (5) and in Fig. 5 can be approximated as 0, because it is a small resistance, then $V_D = V_{BC} = -V_{CB}$. The resistance Rsh is large, so that I' is approximated as zero.

Furthermore, since I_L represents the photocurrent proportional to the amount of light incident on the PD (amount of light received by the PD), and since the amount of light emitted from the LED is proportional to the current I_E flowing in the LED, I_L can be expressed as $I_L = \gamma^* I_E$, where γ^* is the proportionality constant. Then, we obtain the Eq. (3) from Eq. (5).

3. Derivation of AC-based F Parameters

3.1. Equivalent Circuit of PTT Emitter Common with PTT-h Parameter

From the viewpoint of the AC current, we consider that the circuit of Fig. 3 is equivalent to the one in Fig. 6 (a). Also, this circuit of Fig. 6 (a) can be represented as the equivalent circuit with PTT-h parameter (that stands for the h parameter of PTT) as shown in Fig. 6 (b).

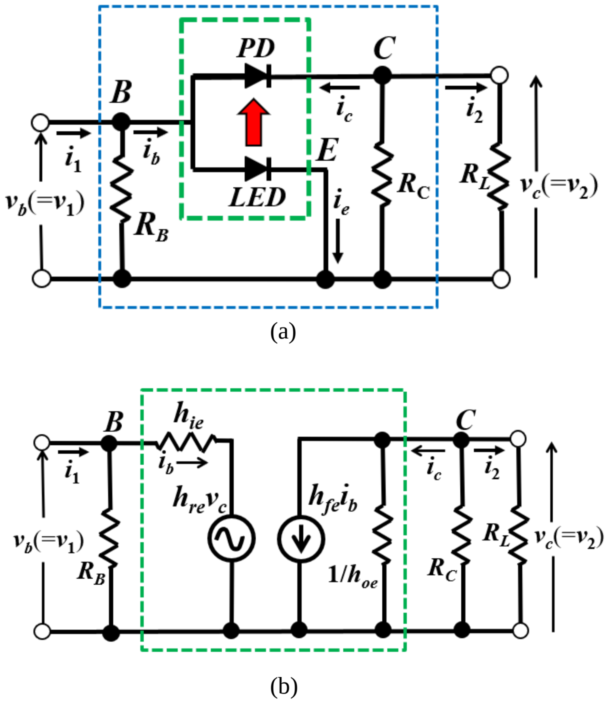


Fig. 6. Equivalent circuit of PTT emitter common circuit with fixed bias for AC small signal amplification. (a) AC small signal amplifier equivalent to the circuit in Fig. 3. (b) Equivalent circuit with PTT-h parameters.

3.2. Representation of AC-based F Matrix Using PTT-h Parameter

The **F** Matrix for two-terminal pair circuit is defined in the form as shown in Eq. (6), which stands for the relation between the input AC voltage and current ($\boldsymbol{v}_1$, $\boldsymbol{i}_1$) and the output ($\boldsymbol{v}_2$, $\boldsymbol{i}_2$). The set of components of **F** Matrix $\{A, B, C, D\}$ are called **F** parameter.

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A, & B \\ C, & D \end{bmatrix} \cdot \begin{bmatrix} v_2 \\ i_2 \end{bmatrix} \equiv \mathbf{F} \cdot \begin{bmatrix} v_2 \\ i_2 \end{bmatrix} \tag{6}$$

On the other hand, using PTT-h parameters of the hybrid matrix in the form of Eq. (1), we have the following matrix equation.

$$\begin{bmatrix} v_b \\ i_b \end{bmatrix} = \begin{bmatrix} \left(\frac{-h_{ie}\cdot h_{oe}}{h_{fe}} + h_{re}\right), & \left(\frac{h_{ie}}{h_{fe}}\right) \\ \left(\frac{-h_{oe}}{h_{fe}}\right), & \left(\frac{1}{h_{fe}}\right) \end{bmatrix} \cdot \begin{bmatrix} v_c \\ i_c \end{bmatrix} \tag{7}$$

From the equivalent circuit in Fig. 6 (b), we have the following Eq. (8).

$$\begin{cases} \begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} v_b \\ \frac{v_b}{R_B} + i_b \end{bmatrix} = \begin{bmatrix} 1, & 0 \\ \frac{1}{R_B}, & 1 \end{bmatrix} \cdot \begin{bmatrix} v_b \\ i_b \end{bmatrix} \\ \begin{bmatrix} v_c \\ i_c \end{bmatrix} = \begin{bmatrix} v_2 \\ \frac{-(R_C+R_L)i_2}{R_C} \end{bmatrix} = \begin{bmatrix} 1, & 0 \\ 0, & \frac{-(R_C+R_L)}{R_C} \end{bmatrix} \cdot \begin{bmatrix} v_2 \\ i_2 \end{bmatrix} \end{cases} \tag{8}$$

Therefore, substituting the Eq. (8) into Eq. (7), we have the **F** Matrix as follows.

$$\mathbf{F} = \begin{bmatrix} 1, & 0 \\ \frac{1}{R_B}, & 1 \end{bmatrix} \cdot \begin{bmatrix} \left(\frac{-h_{ie}\cdot h_{oe}}{h_{fe}} + h_{re}\right), & \left(\frac{h_{ie}}{h_{fe}}\right) \\ \left(\frac{-h_{oe}}{h_{fe}}\right), & \left(\frac{1}{h_{fe}}\right) \end{bmatrix} \cdot \begin{bmatrix} 1, & 0 \\ 0, & \frac{-(R_C+R_L)}{R_C} \end{bmatrix}$$

$$= \begin{bmatrix} \left(\frac{-h_{ie}\cdot h_{oe}}{h_{fe}} + h_{re}\right), & \frac{-(R_C+R_L)}{R_C}\cdot\left(\frac{h_{ie}}{h_{fe}}\right) \\ \left(\frac{1}{R_B}\right)\cdot\left(\frac{-h_{ie}\cdot h_{oe}}{h_{fe}} + h_{re}\right) + \left(\frac{-h_{oe}}{h_{fe}}\right), & \left(\frac{-(R_C+R_L)}{R_C h_{fe}}\right)\cdot\left(\left(\frac{h_{ie}}{R_B}\right)+1\right) \end{bmatrix} \tag{9}$$

3.3. PTT-h Parameter from the VI Characteristic of LED and PD

In this section, based on the abovementioned VI characteristic equations of LED and PD, we derive the concrete PTT-h parameter of PTT emitter common circuit for AC small signal amplifier that can be seen in the AC-based **F** Matrix in Eq. (9).

First, as for h_{re} ($=\partial V_{BE}/\partial V_{CE}$), it is the value of partial differentiation of V_{BE} by V_{CE} under the condition that I_B =constant. Then, we find the following relation between h_{re} and h_{oe}.

$$h_{re} = \left.\frac{\partial V_{BE}}{\partial V_{CE}}\right|_{I_B} = \left(\frac{\partial V_{BE}}{\partial I_E}\right)\left(\frac{\partial I_E}{\partial I_C}\right)\left(\frac{\partial I_C}{\partial V_{CE}}\right) = \left(\frac{\partial I_E}{\partial V_{BE}}\right)^{-1}\cdot\left(\frac{\partial I_E}{\partial I_C}\right)\cdot h_{oe} \tag{10}$$

As for the part of $\partial I_E/\partial V_{BE}$, we have

$$\frac{\partial I_E}{\partial V_{BE}} = \frac{\partial I_{E0}\left(\exp\left(c_{LED}V_{BE}\right)-1\right)}{\partial V_{BE}} = c_{LED}\cdot I_{E0}\exp\left(c_{LED}V_{BE}\right) \tag{11}$$

Since $I_E = I_B + I_C$,

$$\left(\frac{\partial I_E}{\partial I_C}\right) = \left(\frac{\partial (I_B + I_C)}{\partial I_C}\right) = 1 \tag{12}$$

then we have

$$h_{re} = \frac{h_{oe}}{c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \tag{13}$$

As for h_{fe} ($=\partial I_C/\partial I_B$), using the relation $I_E = I_B + I_C$, we transform the Eq. (3) as in the following.

$$\begin{aligned} I_C &= \gamma^* I_E - I_{C0}\left(\exp\left(c_{PD} V_{BC}\right) - 1\right) \\ &= \gamma^* (I_B + I_C) - I_{C0}\left(\exp\left(c_{PD} V_{BC}\right) - 1\right) \end{aligned} \tag{14}$$

Then, we have

$$I_C = \frac{\gamma^* I_B}{1-\gamma^*} - \frac{I_{C0}\left(\exp\left(c_{PD} V_{BC}\right) - 1\right)}{1-\gamma^*} \tag{15}$$

Furthermore, since $V_{BC} = -V_{CB} = -(V_{CE} - V_{BE})$, we obtain the following Eq. (12).

$$I_C = \frac{\gamma^* I_B}{1-\gamma^*} - \frac{I_{C0}\left(\exp\left(-c_{PD} V_{CE}\right) \cdot \exp\left(c_{PD} V_{BE}\right) - 1\right)}{1-\gamma^*} \tag{16}$$

From the Eq. (16), we have the h_{fe} ($=\partial I_C/\partial I_B$) as follows.

$$\begin{aligned} h_{fe} &= \frac{\gamma^*}{1-\gamma^*} - \frac{I_{C0}}{1-\gamma^*} \cdot \exp\left(-C_{PD} V_{CE}\right) \cdot \left(\frac{\partial \exp\left(C_{PD} V_{BE}\right)}{\partial I_B}\right) \\ &= \frac{\gamma^*}{1-\gamma^*} - \frac{I_{C0}}{1-\gamma^*} \cdot \exp\left(-C_{PD} V_{CE}\right) \cdot \left(\frac{\partial \exp\left(C_{PD} V_{BE}\right)}{\partial V_{BE}} \cdot \frac{\partial V_{BE}}{\partial I_B}\right) \\ &= \frac{\gamma^*}{1-\gamma^*} - \frac{I_{C0}}{1-\gamma^*} C_{PD} \cdot \exp\left(C_{PD} V_{BC}\right) \cdot h_{ie} \end{aligned} \tag{17}$$

Similarly, from Eq. (16), we have h_{oe} ($=\partial I_C/\partial V_{CE}$) as shown in the following Eq. (18).

$$\begin{aligned} h_{oe} &= \frac{\partial I_C}{\partial V_{CE}} = \left(\frac{-I_{C0}}{1-\gamma^*}\right) \cdot \frac{\partial\left(\exp\left(c_{PD} V_{BE}\right) \cdot \exp\left(-c_{PD} V_{CE}\right)\right)}{\partial V_{CE}} \\ &= \left(\frac{c_{PD} I_{C0}}{1-\gamma^*}\right)\left\{1 - \left(\frac{\partial V_{BE}}{\partial V_{CE}}\right)\right\} \exp\left(c_{PD} V_{BC}\right) \\ &= \frac{c_{PD} \cdot I_{C0} \exp\left(c_{PD} V_{BC}\right)}{(1-\gamma^*)} \cdot \left\{1 - h_{re}\right\} \end{aligned} \tag{18}$$

As for h_{ie} ($= \partial V_{BE}/\partial I_B$), using the ($\partial I_E/\partial V_{BE}$) in Eq. (11), we have the following Eq. (19).

$$\begin{aligned} h_{ie} &= \frac{\partial V_{BE}}{\partial I_B} = \left(\frac{\partial V_{BE}}{\partial I_E}\right)\left(\frac{\partial I_E}{\partial I_B}\right) = \left(\frac{\partial I_E}{\partial V_{BE}}\right)^{-1}\left(\frac{\partial (I_C + I_B)}{\partial I_B}\right) \\ &= \left(\frac{\partial I_E}{\partial V_{BE}}\right)^{-1}\left(h_{fe} + 1\right) = \frac{\left(h_{fe} + 1\right)}{c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \end{aligned} \tag{19}$$

So far, we have obtained the following simultaneous equations for the four parameters, h_{ie}, h_{fe}, h_{re} and h_{oe}.

$$\begin{cases} h_{ie} = \dfrac{\partial V_{BE}}{\partial I_B} = \dfrac{\left(h_{fe} + 1\right)}{c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \\ h_{fe} = \dfrac{\partial I_C}{\partial I_B} = \dfrac{\gamma^*}{1-\gamma^*} - \dfrac{c_{PD} \cdot I_{C0} \exp\left(c_{PD} V_{BC}\right) \cdot h_{ie}}{1-\gamma^*} \\ h_{oe} = \dfrac{\partial I_C}{\partial V_{CE}} = \dfrac{c_{PD} \cdot I_{C0} \exp\left(c_{PD} V_{BC}\right)}{(1-\gamma^*)} \cdot \left\{1 - h_{re}\right\} \\ h_{re} = \dfrac{\partial V_{BE}}{\partial V_{CE}} = \dfrac{h_{oe}}{c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \end{cases} \tag{20}$$

From the above Eq. (20), we can see the recursive relation between h_{ie} and h_{fe}, and another recursive one between h_{re} and h_{oe}. Then, we derive each of those parameters in the details, from the recursive pairs.

As for h_{fe} and h_{ie}, Eq. (13) and Eq. (15) are integrated into one equation with respect to h_{fe}, we have

$$\begin{aligned} h_{fe} &= \frac{\gamma^*}{1-\gamma^*} - \frac{I_{C0}}{1-\gamma^*} c_{PD} \cdot \exp\left(c_{PD} V_{BC}\right) \cdot h_{ie} \\ &= \frac{\gamma^*}{1-\gamma^*} - \frac{I_{C0}}{1-\gamma^*} \cdot \frac{c_{PD} \cdot \exp\left(c_{PD} V_{BC}\right) \cdot \left(h_{fe} + 1\right)}{c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \end{aligned} \tag{21}$$

In order to solve the Eq. (21) with respect to h_{fe}, we define K as follows.

$$K = \frac{c_{PD} \cdot I_{C0} \exp\left(c_{PD} V_{BC}\right)}{(1-\gamma^*) c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \tag{22}$$

Then, using the K, h_{fe} and h_{ie} can be represented as follows.

$$h_{fe} = \left(\frac{\gamma^*}{1-\gamma^*} - K\right) \cdot \left(1 + K\right)^{-1} \tag{23}$$

$$h_{ie} = \frac{\left(\left(\dfrac{\gamma^*}{1-\gamma^*} - K\right) \cdot \left(1 + K\right)^{-1} + 1\right)}{c_{LED} \cdot I_{E0} \exp\left(c_{LED} V_{BE}\right)} \tag{24}$$

Similarly, as for h_{re} and h_{oe}, Eq. (13) and Eq. (14) are integrated into one equation with respect to h_{re} using K as in the following.

$$h_{re} = \frac{c_{PD} \cdot I_{C0} \exp(c_{PD} V_{BC})}{(1-\gamma^*)} \cdot \frac{\{1-h_{re}\}}{c_{LED} \cdot I_{E0} \exp(c_{LED} V_{BE})} = K \cdot \{1-h_{re}\} \tag{25}$$

Solving for h_{re} in Eq. (21) using K, we obtain another representation of the equations for h_{re} and h_{oe}, such as Eq. (26) and Eq. (27), respectively.

$$h_{re} = \frac{K}{1+K} \tag{26}$$

$$h_{oe} = \frac{c_{PD} \cdot I_{C0} \exp(c_{PD} V_{BC})}{(1-\gamma^*) \cdot (1+K)} \tag{27}$$

In the case of the PTT emitter common circuit with fixed bias as shown in Fig. 3, suppose when the circuit system has no AC component (i.e., $v_i = 0$) and $\gamma^* = R_B / (R_B + R_C)$, there exists a DC power supply voltage V^* such that $V_{BC} = 0$ and the DC current amplification factor $h_{FE} = \gamma^*/(1 - \gamma^*)$ ([13], [14]).

In this case where $V = V^*$, the value of $\exp(c_{PD} V_{BC})$ will be approximately equal to 1.0, even when the AC component is added in the circuit (i.e., $v_i \neq 0$).

Also in this case, based on our experimental results that $\gamma^* = 0.99$, $I_E = 0.2$[A], and that $I_{C0} = 10^{-14}$, $c_{PD} = c_{LED}$ from , the K approximately equals 0 as shown in the following computation.

$$K = \frac{c_{PD} \cdot I_{C0} \exp(c_{PD} V_{BC})}{(1-\gamma^*) c_{LED} \cdot I_{E0} \exp(c_{LED} V_{BE})} \cong \frac{c_{PD} \cdot I_{C0} \exp(0)}{(1-\gamma^*) c_{LED} \cdot I_E} = \frac{I_{C0}}{(1-\gamma^*) \cdot I_E} = \frac{10^{-14}}{(1-0.99) \times 0.2} = 5 \times 10^{-12} \approx 0 \tag{28}$$

As a result, when $V = V^*$ and K nearly equals 0, and so that we have more simplified representation on the four PTT-h parameters (h_{ie}, h_{re}, h_{fe}, h_{oe}) as in the following.

$$\begin{cases} h_{ie} \cong \dfrac{1}{(1-\gamma^*) \cdot c_{LED} \cdot \overline{I_E}} \\ h_{fe} \cong \dfrac{\gamma^*}{1-\gamma^*} = h_{FE}, \quad h_{re} \cong 0, \quad h_{oe} \cong 0 \end{cases} \tag{29}$$

Those values in Eq. (29) are corresponding to the simplified equivalent circuit of BJT (see Fig. 2 (b)). In this case when K nearly equals 0 and Eq. (29) holds, we find out that the amplification factor of AC current h_{fe} is approximately equal to that of DC current h_{FE}.

3.4. Simplified F Matrix and Amplification Degree

As aforementioned, when K nearly equals 0, we obtain the simplified **F** Matrix as follows.

$$\mathbf{F} \cong \begin{bmatrix} 0, & \dfrac{-(R_C+R_L)}{R_C} \cdot \left(\dfrac{h_{ie}}{h_{fe}}\right) \\ 0, & \left(\dfrac{-(R_C+R_L)}{R_C h_{fe}}\right) \cdot \left(\left(\dfrac{h_{ie}}{R_B}\right)+1\right) \end{bmatrix} \tag{30}$$

Since $v_2 = i_2 R_L$ and the bias resistance R_B is much larger than h_{ie} in general, we have Eq. (31).

$$\begin{cases} v_2 = i_2 R_L \cong \left(\dfrac{-R_C R_L}{(R_C+R_L)}\right) \cdot \left(\dfrac{h_{fe}}{h_{ie}}\right) \cdot v_1 \\ i_2 \cong \left(\dfrac{-R_C h_{fe}}{(R_C+R_L)}\right) \cdot i_1 \end{cases} \tag{31}$$

Let A_i, A_v, A_p denote the amplification degree parameters of current, voltage, and power for AC small signal, respectively. In the case when K nearly equals 0, then the parameters of A_i, A_v, A_p can be derived as shown in the followings.

$$\begin{cases} A_i = \left|\dfrac{i_2}{i_1}\right| = \left(\dfrac{R_C}{(R_C+R_L)}\right) \cdot h_{fe} \\ A_v = \left|\dfrac{v_2}{v_1}\right| = \left(\dfrac{h_{fe}}{h_{ie}}\right) \cdot \left(\dfrac{R_C R_L}{(R_C+R_L)}\right) \\ A_p = \left|\dfrac{i_2 \cdot v_2}{i_1 \cdot v_1}\right| = A_i \cdot A_v = \dfrac{(h_{fe})^2}{R_L h_{ie}} \cdot \left(\dfrac{R_C R_L}{(R_C+R_L)}\right)^2 \end{cases} \tag{32}$$

Moreover, using the term of emitter resistance r_e and c_{LED} $(=(m_1 \cdot k \cdot T_{LED}/q)^{-1} = (m_1 \cdot V_T)^{-1})$ where V_T $(= k \cdot T_{LED}/q)$ is thermal voltage, the h_{ie} can be differently represented as in the following.

$$\begin{cases} r_e := \dfrac{1}{c_{LED} \cdot \overline{I_E}} = \dfrac{1}{\left(\dfrac{m_1 k T_{LED}}{q}\right)^{-1}} \cdot \dfrac{1}{\overline{I_E}} = \dfrac{m_1 V_T}{\overline{I_E}} \\ h_{ie} \cong \left(\dfrac{1}{1-\gamma^*}\right) \cdot \left(\dfrac{1}{c_{LED} \cdot \overline{I_E}}\right) = \left(\dfrac{r_e}{1-\gamma^*}\right) \end{cases} \tag{33}$$

Substituting the other representation of h_{fe} $(=\gamma^*/1-\gamma^*)$ and h_{ie} $(=r_e/1-\gamma^*)$ into Eq. (30), we have the following simplified form of AC-based **F** Matrix and A_i, A_v, A_p.

$$\mathbf{F} \cong \begin{bmatrix} 0, & \dfrac{-(R_C+R_L)}{R_C} \cdot \left(\dfrac{\gamma^*}{r_e}\right) \\ 0, & \left(\dfrac{-(R_C+R_L)}{R_C}\right) \cdot \left(\dfrac{1-\gamma^*}{\gamma^*}\right) \end{bmatrix} \tag{34}$$

$$\begin{cases} A_i = \left|\dfrac{i_2}{i_1}\right| = \left(\dfrac{R_C}{(R_C+R_L)}\right) \cdot \left(\dfrac{\gamma^*}{1-\gamma^*}\right) \\ A_v = \left|\dfrac{v_2}{v_1}\right| = \left(\dfrac{R_C R_L}{(R_C+R_L)}\right) \cdot \left(\dfrac{\gamma^*}{r_e}\right) \\ A_p = A_i \cdot A_v = \left(\dfrac{1}{(1-\gamma^*) r_e R_L}\right) \cdot \left(\dfrac{\gamma^* R_C R_L}{(R_C+R_L)}\right)^2 \end{cases} \tag{35}$$

4. Conclusion

In this paper, in order to analyze the amplification function of PTT emitter common circuit for AC small signal amplifier, we have newly derived AC-based **F** parameter that stands for the components of **F** Matrix for AC signal, based on the calculation of the PTT-h parameter from the VI characteristic equations of LED and PD.

Furthermore, we have presented that another simplified representation of the AC-based **F** Matrix is possible by practical approximation in the case when K nearly equals 0. We consider that the amplification degree parameters of A_i, A_v, A_p as shown in Eq. (35) are then practically meaningful.

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