Novel Opt-coupling Transistor by LED and PD and its Application

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Abstract

This paper proposes a novel transistor-like device by the optical coupling of LED (Light Emitting Diode) and Photodiode. The device that we call “OCT: Optical Coupling Transistor” shows an amplification function if the Photodiode current by photo electromotive force is feed backed into the LED, in the same way as the case of common emitter circuit of the conventional Bipolar Junction Transistor. In this paper, we present the amplification principle and its applications by OCT such as audio amplifier and operational amplifier.

Keywords: Transistor, Thyristor, Opt-coupling, LED, Photodiode, Optical Coupling Transistor

1. Introduction

It is well known that the bipolar transistor is a semiconductor device capable of amplifying a small electric signal to a significant output level, e.g. of volt-order, in the case of analogue application.

However, as a matter of fact, the transistor itself generates neither a high voltage nor large current. Practically, the bipolar transistor behaves as a variable resistance element whose resistance value between the collector and the emitter can be controlled widely from near zero ohm to almost infinity ohm by a small input current, namely the Base current $I_B$ that is passed from the Base to the Emitter in NPN typed bipolar transistor. As the collector is connected to a resistor $R_C$ in the common emitter transistor circuit, a constant direct current voltage $V_R$ is applied to between $R_C$ and the Emitter. Under such a condition, if $I_B$ is passed from the base to the Emitter then $R_{CE}$, which is the internal resistance between the Collector and the Emitter, will changes drastically. This causes the changes of the collector current $I_C$ and also $V_{CE}$, the output voltage between Collector and Emitter.

One of the authors, Kensho Okamoto has noticed the behavior of the bipolar junction transistor as an electronically controllable resistor and so he thought that it might be possible to realize a new amplifier device by a system combining LED and silicon photodiode, or silicon solar cell, with positive feedback manner. In this paper, we call the device “OCT” that stands for Optical-Coupling typed Transistor. Further-more, we show the fact that the OCT can become a thyristor-like switching device under a certain condition.

According to our literature search, there are only two similar researches elsewhere in the world other than ours. However no practical devices were developed in their works.

2. Transistor by Photo-Coupling

The bipolar junction transistor was invented in 1948. As is well known, there are two types in the bipolar transistor, i.e. PNP and NPN transistors. Since the birth
of transistor, the operation of such bipolar transistors have been explained by the behavior of electrons and positive holes in the Emitter(E), Base(B) and Collector(C) regions as illustrated in Fig.1 (a).

However, in 1989, B.J. Van Zeghbroeck et.al have proposed the notion of “Photon transport transistor”.\(^1\) And in 1996, W. N. Cheung and P. J. Edwards have theoretically shown the characteristics of class of opto-coupler amplifier.\(^2\)

On the other hand, as mentioned before, Okamoto who is one of the authors of this paper, also has found recently that the well-known common base transistor circuit in Fig.1 (a) can be realized by putting together an infrared light-emitting diode (IR-LED) and a Si photodiode (Si-PD) as shown in Fig.1 (b).

Then he made the quasi emitter common transistor circuit using IR-LED and Si-PD as shown in Fig.2 (b) in order to confirm whether the circuit operated as the real transistor amplifier shown in Fig.2 (a).\(^3\)\(^4\) Fig.3 (a) shows an example of the device which consists of an IR-LED and Si-PD. Fig.3 (b) shows picture of actual OCT module. Amplification factor \(\alpha\), which is defined as \(I_C/I_E\) shown in Fig.3 (b), our first OCT was about 0.34.

\[\alpha = 0.99\] is of conventional transistor. According to the transistor theory, if \(\alpha = 0.9\), then it is possible to build an emitter-common transistor with \(\beta = 9\). This means that the LED-photodiode system can be used as an amplifier, in a similar way as the bipolar transistor.

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3. Amplification Function

In this section, we explain about the amplification principle of the OCT. In the circuit of Fig. 7, $I_C$ does not flow because the voltage direction of PD is reversely applied by the relation of connection to voltage source $V$.

As shown in Fig. 8, Base-current $I_B$ flows through the LED connected between B to E when the switch SW2 is turned on. Hence,

$$I_E = I_B \quad \text{(when } I_B \text{ flows)} \quad (2)$$

Then, the LED emits light and the LED light enters into the PD, because the LED and the PD is optically faced each other. Consequently, photovoltaic effect occurs in PD and the photocurrent $I_C$ generates and flows through RC and the PD. The $\alpha$ is defined as the ratio of the current flowing through the PD and the current owing through the LED as shown in Eq. (3).

$$\alpha = \frac{I_C}{I_E} \quad (3)$$

Therefore, $I_C$ is expressed as Eq. (4).

$$I_C = \alpha \cdot I_E \quad (4)$$

At this time, $I_E = I_B$, as shown in Eq.(2). Then, Eq.(4) can be expressed as Eq.(5).

$$I_C = \alpha \cdot I_B \quad (5)$$

At the next stage, the current $I_C$ flows into LED, then $I_E$ will increase by the current, and at this point, it becomes $I_E = I_B + I_C = I_B + \alpha I_B$. And then, the light intensity of the LED increases by $\alpha I_B$, so $I_C$ increases more by $\alpha \cdot \alpha I_B$. Accordingly, at this point, $I_C$ becomes the current as shown in Eq.(6).

$$I_C = \alpha I_B + \alpha \cdot \alpha I_B \quad (6)$$

In a similar way, we have the following equations.

$$I_C = \alpha I_B + \alpha \cdot \alpha I_B + \alpha(\alpha^2 I_B) + \cdots \quad (7)$$
In Eq.(8), the term \((\alpha + \alpha^2 + \alpha^3 + \cdots)\) is a well-known infinite progression and its sum becomes the value as shown in Eq.(9), if \(\alpha\) is \(0 \leq \alpha < 1\).

\[
\left(\alpha + \alpha^2 + \alpha^3 + \cdots\right) = \frac{\alpha}{1-\alpha} \tag{9}
\]

Eventually, \(I_C\) becomes as follows.

\[
I_C = \frac{\alpha I_B}{1-\alpha} \tag{10}
\]

The ratio of \(I_B\) and \(I_C\) is as shown in Eq.(11).

\[
\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} \tag{11}
\]

In Eq.(10), if \(\alpha = 0.5\) then \(\beta = 0.5\). However, if \(\alpha = 0.9\) then \(\beta = 9\). If \(\alpha\) exceeds 0.9, \(\beta\) enhances greatly e.g. \(\alpha = 0.99, \beta = 99\).

On other hand, in case of \(\alpha \geq 1\),

\[
I_C = +\infty \tag{12}
\]

In this case, as a matter of fact, the suitable resistance \(R_c\) suppresses the increase of the current \(I_C\), and so the \(I_C\) becomes stable. In this stable situation, even when the switch SW2 is turned off, the current \(I_C\) continues to flow at the same value. This seems that the OCT can become a thyristor-like device.

4. Variations

4.1. Other combination

Fig.9 shows the measurement circuit of quasi common base circuit using OCT. The light intensity and the wavelength of LED and photocurrent of PD are very important in OCT. As shown in Fig.10, light emission wavelength of the LED (940nm) and light reception of the PD (960nm) are almost identical. For this reason, we were using only infrared LED, looking for the best opt-coupling conditions.

However, we have tried to make an OCT using high luminous efficiency red LED as another combination of photo-coupling (Fig.11). The electrical characteristic of this OCT was much better than we thought.

The amplification factor \(\alpha\) using OCT that consists of IR-LED and PD as shown in Fig.12. The \(\alpha\) significantly varies depending on the LED current \(I_{LED}\) when \(I_{LED}\) less than about 200mA. Fig.13 shows the \(\alpha\) using OCT consists of red-LED and PD. It is stable when the \(I_{LED}\) is greater than a few 10mA.
4.2. Operational amplifier

We have also made an operational amplifier using OCT module as shown in Fig.14. Moreover, we have confirmed that the Operational Amplifier in Fig.14 works as well as the conventional operational amplifier (Fig.15).

5. Conclusion

We have presented a novel transistor OCT by opt-coupling of LED and PD. There are still rooms for improvement in realizing efficient transistors by the coupling. However, there is a high possibility that the OCT that we have proposed in this paper, can be applied to develop a various kinds of practical devices, not only the power transistors such as thyristor, but also switching devices. We consider that the OCT will be very promising in the future.

6. References