A NOVEL INTERPRETATION OF TRANSDUCER POWER GAIN BY OPTICAL ANALOGY

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ABSTRACT: A novel interpretation of transducer power gain (G_T) is presented by optical analogy. By employing scattering parameters of the input / output matching network and the transistor, we have developed a simple method to derive G_T . In addition to simplicity, our theory also has the advantage of giving the physical meaning for each term of the formula of G_T . © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 31: 124–126, 2001.

Key words: transducer power gain; scattering parameters; transistor

INTRODUCTION

It is well known that the transducer power gain (G_T) is one of the most important figures of merit in the design of microwave transistor amplifiers. Several methods [1–4] have been proposed to derive the transducer power gain. However, most of them rely heavily on mathematical calculations rather than simple physical reasoning, and therefore it is difficult to give a physical meaning to each term in the formula of the transducer power gain G_T . In view of this, we have developed a simple and intuitive way to derive G_T by means of optical analogy. In the derivation, the concept of incident and reflected waves is employed to simplify the circuit analysis, and the physical insight into each term in G_T is naturally obtained. Our theory also provides a useful transformation between the different methodologies of optics and microwave circuit design.

THEORY

The block diagram of a microwave transistor amplifier is shown in Figure 1(a), where V_S is the voltage source, Z_O is 50 Ω , and Γ_S and Γ_L are the source and load reflection coefficients in a Z_O system. P_{AVS} and P_L represent the available power of the signal source and the power delivered to the load Z_O , respectively. The input and output matching networks are assumed to be passive and lossless.

In order to obtain the transducer power gain, i.e., P_L/P_{AVS} , by optical analogy, we first replace components in the microwave circuit by optical components. The resultant optical system is shown in Figure 1(b), where the signal source in the amplifier has been replaced by a light source with power of P_{AVS} , the input matching network by a lossless partially transmitting mirror with a reflection coefficient of Γ_S (at plane 2) looking toward the source, the output matching network by a lossless partially transmitting mirror with a

reflection coefficient of Γ_L (at plane 5) looking toward the load, and finally, the transistor by an optical gain medium with the scattering parameters of the transistor. Note that Z_O s, because of their nonreflecting property in a Z_O system, were replaced by empty space in this optical system. Also note that Γ_S , in fact, is the S_{22} of the input mirror and Γ_L is the S_{11} of the output mirror. Because any linear network that contains no controlled sources will be reciprocal [5], the S -matrix of the input/output matching network will be symmetric [6]. Further, owing to the lossless property of the input/output matching network, the S -matrix is also unitary [6]. It is proven that the magnitudes of S_{11} and S_{22} of a symmetric network will be equal [7], and hence the magnitude of the reflection coefficient Γ'_S (i.e., S_{11}) of the input mirror at plane 1 looking toward the load is equal to that of Γ_S , namely,

$$|\Gamma'_S| = |\Gamma_S|. \quad (1)$$

Equation (1) is the key point of our proposed theory. The S -matrix of the input mirror can be easily derived from (1) due to its lossless and unitary properties [6, 7] as follows:

$$[S]_{\text{input}} = \begin{bmatrix} \Gamma'_S & \sqrt{1 - |\Gamma'_S|^2} e^{j\phi_1} \\ \sqrt{1 - |\Gamma_S|^2} e^{j\phi_1} & \Gamma_S \end{bmatrix} \quad (2)$$

where ϕ_1 is an arbitrary phase angle. Similarly, the S -matrix of the output mirror can be written as

$$[S]_{\text{output}} = \begin{bmatrix} \Gamma_L & \sqrt{1 - |\Gamma_L|^2} e^{j\phi_2} \\ \sqrt{1 - |\Gamma'_L|^2} e^{j\phi_2} & \Gamma'_L \end{bmatrix} \quad (3)$$

where ϕ_2 is another arbitrary phase angle.

When the light source with power P_{AVS} is incident from the left on the input mirror as shown in Figure 1(b), it is partially reflected and partially transmitted. According to basic electromagnetic theory [8], the transmitted power is

$$|a_1|^2 = P_{AVS} \times (1 - |\Gamma'_S|^2) = P_{AVS} \times (1 - |\Gamma_S|^2) \quad (4)$$

where a_1 is the normalized amplitude of the transmitted light. However, this transmitted light continues to the optical gain medium. Here, the portion $S_{11} \cdot a_1$ is reflected, and the portion $S_{21} \cdot a_1$ is transmitted. The reflected part is returned to the input mirror and then reflected: $\Gamma_S \cdot S_{11} \cdot a_1$. This amplitude, reflected from the input mirror, goes through the same process as the initially transmitted light a_1 . Each repetition of the process amounts to multiplication by $\Gamma_S \cdot S_{11}$. Therefore, the total wave leaving the input mirror and incident on the gain medium (see Fig. 2) is

$$a = a_1 (1 + \Gamma_S \cdot S_{11} + (\Gamma_S \cdot S_{11})^2 + \dots) = \frac{a_1}{1 - \Gamma_S \cdot S_{11}} \quad (5)$$

where a is the normalized amplitude of the total wave. Since the power of a wave is the square of its amplitude, the actual

Figure 1 (a) Block diagram of a microwave amplifier. (b) Optical analogy of the microwave amplifier circuit in (a)

Figure 2 Schematic diagram showing the wave reflections between the transistor and the input mirror

power incident into the gain medium is

$$|a|^2 = \frac{|a_1|^2}{|1 - \Gamma_S \cdot S_{11}|^2} = P_{AVS} \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_S \cdot S_{11}|^2}. \quad (6)$$

From the definition of S_{21} , the power coming out of the gain medium can be easily written as

$$|a_2|^2 = |a \cdot S_{21}|^2 = P_{AVS} \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_S \cdot S_{11}|^2} |S_{21}|^2 \quad (7)$$

where a_2 is the normalized amplitude of the light just coming out of the gain medium. When a_2 arrives at the output mirror, a portion $\Gamma_L \cdot a_2$ is reflected. The reflected part is returned to the gain medium, where a portion $S_{22} \cdot \Gamma_L \cdot a_2$ is reflected and a portion $S_{12} \cdot \Gamma_L \cdot a_2$ is transmitted. The transmitted part continues to the input mirror, and is reflected: $\Gamma_S \cdot S_{12} \cdot \Gamma_L \cdot a_2$. This reflected wave experiences multiple reflections between the input mirror and the gain medium, and finally, a total wave incident on the gain medium is $\Gamma_S \cdot S_{12} \cdot \Gamma_L \cdot a_2 / (1 - \Gamma_S \cdot S_{11})$, which is then transmitted through the

gain medium with an amplitude of $S_{21} \cdot \Gamma_S \cdot S_{12} \cdot \Gamma_L \cdot a_2 / (1 - \Gamma_S \cdot S_{11})$. This amplitude has to be added to the initial reflected wave $S_{22} \cdot \Gamma_L \cdot a_2$, and their sum becomes

$$\begin{aligned} & S_{22} \cdot \Gamma_L \cdot a_2 + \frac{S_{21} \cdot \Gamma_S \cdot S_{12} \cdot \Gamma_L \cdot a_2}{1 - \Gamma_S \cdot S_{11}} \\ &= \left(S_{22} + \frac{S_{21} \cdot \Gamma_S \cdot S_{12} \cdot \Gamma_L \cdot a_2}{1 - \Gamma_S \cdot S_{11}} \right) \cdot \Gamma_L \cdot a_2 \\ &= \Gamma_{\text{out}} \cdot \Gamma_L \cdot a_2 \end{aligned} \quad (8)$$

where Γ_{out} is defined as $S_{22} + S_{21} \cdot \Gamma_S \cdot S_{12} / (1 - \Gamma_S \cdot S_{11})$. This summed reflected wave in (8) goes through the same process as the initially transmitted light a_2 . Clearly, each repetition of the process amounts to multiplication by $\Gamma_{\text{out}} \cdot \Gamma_L$. Therefore, the total wave leaving the gain medium and incident on the output mirror (see Fig. 3) is

$$a_3 = a_2 \left(1 + \Gamma_{\text{out}} \cdot \Gamma_L + (\Gamma_{\text{out}} \cdot \Gamma_L)^2 + \dots \right) = \frac{a_2}{1 - \Gamma_{\text{out}} \cdot \Gamma_L} \quad (9)$$

and its associated power is

$$\begin{aligned} |a_3|^2 &= \left| \frac{a_2}{1 - \Gamma_{\text{out}} \cdot \Gamma_L} \right|^2 \\ &= P_{\text{AVS}} \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_S \cdot S_{11}|^2} |S_{21}|^2 \frac{1}{|1 - \Gamma_{\text{out}} \cdot \Gamma_L|^2} \end{aligned} \quad (10)$$

where a_3 is the normalized amplitude of the total wave incident on the output mirror. Since the reflection coefficient of the output mirror is Γ_L , it is clear that the power P_L coming out from the output mirror is

$$\begin{aligned} P_L &= |a_3|^2 (1 - |\Gamma_L|^2) \\ &= P_{\text{AVS}} \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_S \cdot S_{11}|^2} |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - \Gamma_{\text{out}} \cdot \Gamma_L|^2}. \end{aligned} \quad (11)$$

P_L corresponds to the power delivered to the load in the microwave amplifier, and hence from the above equation

Figure 3 Schematic diagram showing the wave reflections between the transistor and the output mirror, as well as those between the transistor and the input mirror

(11), the transducer power $G_T = P_L / P_{\text{AVS}}$ can be found to be

$$G_T = \frac{1 - |\Gamma_S|^2}{|1 - S_{11} \Gamma_S|^2} |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - \Gamma_{\text{out}} \Gamma_L|^2}. \quad (12)$$

CONCLUSION

A novel interpretation of the formula of transducer power gain was presented. The derivation was based on the scattering parameters of the input/output matching network and the transistor and optical system associated with them. It was found that $1 - |\Gamma_S|^2$ represents the fraction that the signal power transmits through the input matching network, and $1 / |1 - \Gamma_S \cdot S_{11}|^2$ accounts for the multiple reflections of the transmitted wave between the input matching network and the transistor. $|S_{21}|^2$ is the power gain of the transistor. $1 / |1 - \Gamma_L \cdot \Gamma_{\text{out}}|^2$ takes into account the multiple reflections between the transistor and the output matching network, as well as those between the input matching network and the transistor.

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IMPROVEMENT OF MODULATION / SWITCHING PERFORMANCES BY USING A TWO-SECTION SEMICONDUCTOR OPTICAL AMPLIFIER

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ABSTRACT: By optimizing the carrier distribution along the longitudinal axis of a two-section semiconductor optical amplifier (SOA), we have improved the modulation / switching performances (modulation index and efficiency, switching contrast) with respect to those of a single-section component. The modulation efficiency has been raised by up to 137%. © 2001 John Wiley & Sons, Inc. *Microw Opt Technol Lett* 31: 126–129, 2001.

Key words: semiconductor optical amplifiers; modulation; switching; two-section SOA