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Relationship Between Noise Figure and Equivalent Input Noise Current Spectral Density for Optical Receiver Design*

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Abstract: Based on the equivalent circuit model of a two-port optical receiver front-end, the relationship between the equivalent input noise current spectral density and the noise figure is analyzed. The derived relationship has universal validity for determining the equivalent input noise current spectral density for optical receiver designs, as verified by measuring a 155Mb/s high-impedance optical receiver front-end. Good agreement between calculated and simulated results has been achieved.

Key words: optical receiver; noise figure; equivalent input noise current
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1 Introduction

Optical receivers are important components in optical communication systems. The equivalent input noise current spectral density is a key parameter characterizing the noise performance of optical receiver front-ends. Noise figure, a common and useful means of describing the noise performance of a circuit or a device, can be measured directly using a noise figure analyzer. However, the equivalent input noise current spectral density of an optical receiver front-end cannot be measured directly by a noise test set[1~3]. In this paper, we propose a simple but efficient transformation technique to calculate the equivalent input noise current spectral density of an optical receiver front-end using the measured noise figure. This technique is based on the equivalent circuit model of a two-port optical receiver.

2 Theory analysis

Figure 1 shows the equivalent model of an optical receiver front-end. It includes three parts: source, preamplifier, and load. Here i_s is the current source, R_s is the source resistance, Z_i and Z_o are the input and output impedances, respectively, v_i and v_L are the voltages of input and output nodes, respectively, v_o is the equivalent output voltage, and Z_L is the load impedance.

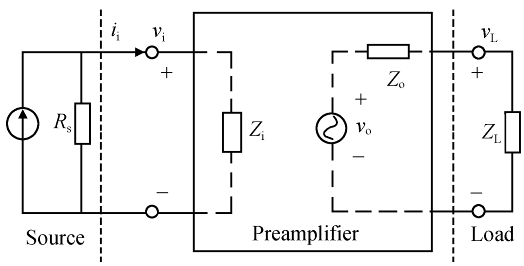

Fig. 1 Equivalent model of optical receiver front-end

The noise factor F of the two-port network is defined by[4,5]

$$F = \frac{\text{total output noise power}}{\text{output noise power due to source resistance}} = \frac{N_o}{G_a N_i} = 1 + \frac{\Delta N}{G_a N_i} \tag{1}$$

where N_i is the available input noise power due to the source resistance, N_o is the total output noise power of the real device, ΔN is the output noise power due to the preamplifier, and G_a is the available power gain at a specific frequency. Expressing this ratio in decibels returns the noise figure NF:

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$$\mathrm{NF} = 10\lg F \tag{2}$$

In Eq.(1), G_a is defined as the ratio of power available from the output of the circuit to the power available from the source[6,7], and it can be expressed as

$$G_a = \frac{P_{ao}}{P_{as}} = \frac{v_o^2/4R_o}{i_s^2 R_s/4} \tag{3}$$

The available input noise power due to source resistance in a narrow bandwidth is

$$N_i = kT_0\Delta f \tag{4}$$

where $k = 1.38\times10^{-23}$ J/K is the Boltzmann constant, $T_0 = 290$K is the standard reference temperature, and Δf is the noise bandwidth.

The available output noise power of the circuit can be expressed in terms of the available output noise voltage as[8]

$$N_o = \frac{\overline{v_{o,noise}^2}}{4R_o} \tag{5}$$

Defining the transimpedance Z_t as the ratio of v_L to i_i, the ratio of v_o to i_s can be expressed in terms of Z_t as

$$\frac{v_o}{i_s} = |Z_t|\left|\frac{R_s}{Z_i + R_s}\right|\left|\frac{Z_L + Z_o}{Z_L}\right| \tag{6}$$

where Z_t and Z_i can be expressed in terms of the Z-parameter of the preamplifier as follows:

$$Z_t = \frac{Z_{21}Z_L}{Z_{22} + Z_L} \tag{7}$$

$$Z_i = Z_{11} - \frac{Z_{21}Z_{12}}{Z_{22} + Z_L} \tag{8}$$

The available voltage v_o can be related to the output voltage v_L by

$$v_L = v_o\left|\frac{Z_L}{Z_o + Z_L}\right| \tag{9}$$

Combining Eq.(3) through Eq.(9) into Eq.(1), simplifying the result, and writing the noise factor in terms of the mean-square value of the output noise voltage $\overline{v_{L,noise}^2}$, we get

$$F = \frac{\overline{v_{L,noise}^2}}{4kT_0\Delta f\,|Z_t|^2\left|\frac{R_s}{R_s + Z_i}\right|^2\frac{1}{R_s}} \tag{10}$$

Therefore, the relationship between the noise factor and the output noise voltage spectral density is

$$\frac{\overline{v_{L,noise}^2}}{\Delta f} = 4kT_0F\,|Z_t|^2\left|\frac{R_s}{R_s + Z_i}\right|^2\frac{1}{R_s} \tag{11}$$

The total equivalent input noise current spectral density can be expressed as follows:

$$\frac{\overline{i_{in,total}^2}}{\Delta f} = \frac{\overline{v_{L,noise}^2}}{\Delta f}\times\frac{1}{|Z_t|^2} = \frac{4kT_0FR_s}{|R_s + Z_i|^2} \tag{12}$$

It consists of contributions from two parts: the preamplifier and the source resistance. The contribution from the source resistance can be expressed as follows:

$$\frac{\overline{i_{in,R_s}^2}}{\Delta f} = \frac{4kT_0R_s}{|R_s + Z_i|^2} \tag{13}$$

Therefore, the equivalent input noise current density caused by the preamplifier is

$$\frac{\overline{i_{in,equ}^2}}{\Delta f} = \frac{(F-1)4kT_0R_s}{|R_s + Z_i|^2} \tag{14}$$

3 Experimental verification

In order to verify the equations derived in Section 2, a high-impedance amplifier for an optical receiver has been characterized.

Figure 2 shows a schematic of a high-impedance preamplifier, which includes two stages. The first stage provides gain, and the second stage is the source follower for output matching. C_1 and C_2 are the DC isolation capacitors at the input and output nets, respectively.

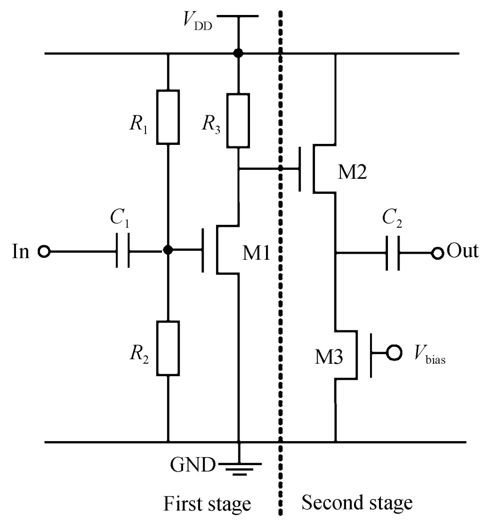

Fig. 2 Schematic of high-impedance preamplifier

The total equivalent input noise current spectral density of the preamplifier is shown in Fig.3. Good agreement can be observed between the simulated and calculated data.

A 155Mb/s preamplifier has been fabricated by using standard 0.6μm CMOS technology, and the chip microphotograph is shown in Fig.4.

Figure 5 shows the measured noise figure and the calculated input impedance versus frequency.

In Fig. 6, the calculated transimpedance and equivalent input noise current density are given.

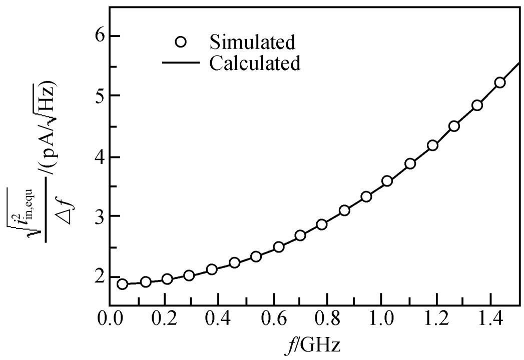

Fig. 3　Comparison of the total equivalent input noise current spectral density

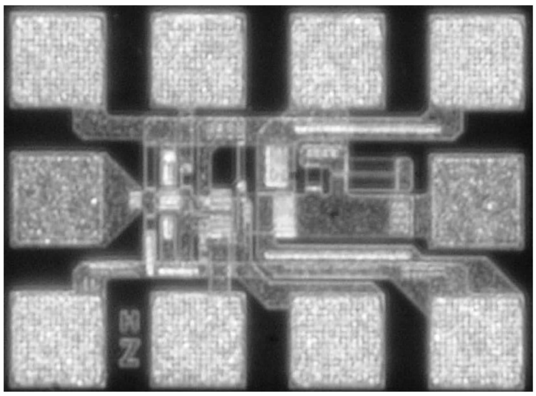

Fig. 4　Chip microphotograph of preamplifier

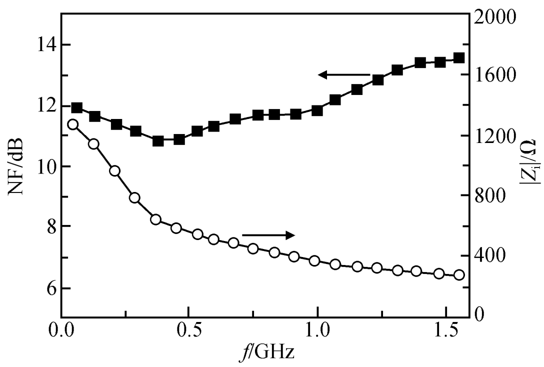

Fig. 5　Noise figure and input impedance versus frequency

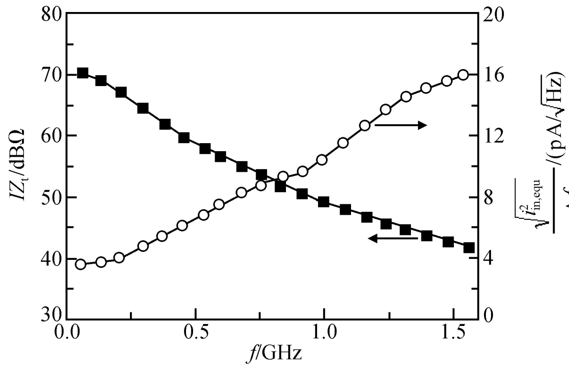

Fig. 6　Transimpedance and the equivalent input noise current spectral density versus frequency

In the figure, the transimpedance Z_t is shown in terms of dBΩ, which is defined by $20\lg|Z_t|$, and the -3dB bandwidth is 150MHz. The equivalent input noise current spectral density is calculated to be $4\text{pA}/\sqrt{\text{Hz}}$ at 150MHz and $11\text{pA}/\sqrt{\text{Hz}}$ at 1GHz.

The measured data are higher than the simulated data, especially at high frequencies. One reason may come from the circuit design and manufacture. In the simulation phase, the foundry does not provide an accurate noise model. There is only a simple MOSFET noise model. Additionally, the parasitic parameter in the layout, such as parasitic capacitor of input resistors, also causes error. Other reasons come from the measurement.

4　Conclusion

In this paper, we have proposed analytical expressions for the relationship between the noise figure and the equivalent input noise current density. This technique is based on the conventional two-port network analytical technique. The validity of the new approach is proved by comparison with simulated and calculated parameters. With this simple transformation technique, the equivalent input noise current spectral density of an optical receiver front-end can be easily calculated.

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光接收机前端等效输入噪声电流谱密度与噪声系数间的关系*

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摘要：根据光接收机前端等效电路模型,建立了噪声系数与等效输入噪声电流谱密度的关系.提出通过测量光接收机前端电路噪声系数间接获得等效输入噪声电流谱密度的方法.155Mb/s 高阻结构光接收机前置放大器的电路仿真与计算验证了推导公式的正确性.最后给出在芯片测试实例.

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