A Low-Current Logarithmic LED Electrometer

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Abstract—A new circuit for measuring low dc currents using an LED-based logarithmic electrometer is presented. The electrometer is designed to measure currents from 1 pA to 0.1 mA. Temperature compensation is achieved using the ratio technique in the temperature range 20 °C–70 °C. Variations in the scale factor as a function of the input current and the device constant \( n \) as a function of temperature are also discussed.

Index Terms—Electrometer, LED, logarithmic amplifier, low current, scale factor, temperature compensation.

I. INTRODUCTION

LOGARITHMIC current electrometers are widely used in many fields such as nuclear instrumentation, vacuum ultraviolet, optical measurements, analog compression, etc. [1]–[4]. Semiconductor junctions exhibit logarithmic relationship between voltage and current over a wide dynamic range. This inherent nonlinearity is so useful that circuits are designed which will work over the widest range of input currents, refining them by such means as range extension, response and temperature compensations. The forward current versus voltage characteristics of the p-n junction of a diode and collector current versus base emitter voltage characteristics of the transistor are commonly used. Their characteristics depend considerably on the temperature. Hence, a temperature compensation arrangement is normally needed to maintain constant output at a given current within a certain temperature range and at wide operating current levels. The current–voltage (I–V) characteristics of a p-n junction deviate from the ideal theory of diffusion for two reasons. One is the ohmic resistance of the diode, which becomes appreciable at high currents, and the other is the recombination generation current, which becomes dominant at lower current [5]. The reverse saturation current \( I_o \) of the diode determines the lower current limit. It is exponentially related to the band gap of the diode. It has been shown that the \( I_o \) of LED’s that are made of wide-band-gap semiconductor material is many orders of magnitude lower than that of silicon devices. This difference increases for wider band gap materials, such as SiC, GaN, etc. The \( I_o \) is estimated to be about \( 10^{-17} \) A or less for LED’s [6]. This property of the LED makes it suitable as a nonlinear element of the log amplifier for low-current measurements. The advantage of these devices is that they are commercially available at very low cost as compared to the low-leakage diodes or transistors. Logarithmic LED electrometers have been designed to measure low currents [7]. Log electrometers with temperature compensation using thermistor and ratio techniques have been reported in the literature [1], [7], [8].

Experimental results [2] show that the ratio technique is superior as compared to the thermistor technique. In the former case extensive device testing is required to select four matched transistors, and the performance of the circuit depends on the matching of various transistor parameters. A log electrometer was designed using low-cost LED’s in place of transistors for measurement of currents from 1 pA to 10 \( \mu \)A [8] in which LED’s were selected from a random lot.

In this paper, a temperature-compensated log ratio amplifier using the LED as a nonlinear element has been designed to measure currents from 1 pA to 0.1 mA. Since matched LED’s are not commercially available, LED’s were selected through extensive device testing from a random lot. The constant \( n \) and the reverse saturation current are important parameters in deciding the I–V characteristics of a diode. Therefore, LED’s having \( n \) within 1% were chosen. A new circuit, which reduces the number of components based on the ratio technique, is described. In a ratio technique, normally four operational amplifiers with four log elements (diodes) are required. However, the proposed circuit uses three operational amplifiers and three log elements. Variation of the scale factor, which denotes the gain, with input current is presented. The circuit has been tested in the temperature range of approximately 20 °C–70 °C and an error <6% is observed for seven decades in this temperature range. It can be shown that deviations at higher temperatures are due to variations of \( n \) with temperature. Hence, the temperature dependence of \( n \) is also discussed. In this paper, we wish to present the theoretical background, error analysis, experiment, and discussion.

II. THEORETICAL BACKGROUND

The experimental circuit is shown in Fig. 1, in which A1 is an operational amplifier, \( D_1 \) is a logarithmic diode (LED), and these compose a logarithmic transfer circuit for the input signal. Operational amplifier A2, LED \( D_2 \) and operational amplifier A3, LED \( D_3 \) form logarithmic amplifiers for two reference channels. A6 and A7 with the temperature-compensated reference diode (ICL 8069) form voltage references. A4 and A5 act as sourcing amplifiers.

Operational amplifiers A1, A2, and A4 form a log ratio amplifier. Its output, \( V_{\text{OUT1}} \), is given by

\[
V_{\text{OUT1}} = V_1 - V_2 = \frac{n_1 kT_1}{q} \ln \left( \frac{I_{\text{th}}}{I_{\alpha}} \right) - \frac{n_2 kT_2}{q} \ln \left( \frac{I_{\text{ref1}}}{I_{\alpha}} \right)
\]

where \( n_1, n_2 \) are device constants and \( T_1, T_2 \) are absolute temperatures of diodes \( D_1 \) and \( D_2 \), respectively, \( k \) is the Boltzman constant.