A quasilinear wide-range radiometer amplifier implemented with correlated phase-sensitive detection

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A radiometer amplifier capable of wide-range optical measurement is described. Based on a novel automatically ranged electrometer and amplifier circuit, the radiometer provides a quasilinear analog output for the measurement of input radiation over ten orders of magnitude. Together with the scheme of phase-sensitive detection of modulated optical signals, the circuit resulted in an output voltage of low noise and offset drift. It can be applied directly to various kinds of photodetectors. The application of standard integrated circuits and lock-in amplifiers makes the whole system low cost and it can be readily built. © 1999 American Institute of Physics. [S0034-6748(99)04905-9]

I. INTRODUCTION

Optical radiometers are the instruments for measuring various kinds of radiation. They are applied in many research areas such as spectroscopy, interferometry, light source characterization, and high-temperature monitoring. For covering different spectral regions, a variety of sensor elements including quantum detectors and thermal detectors are used in the radiometer. The detector element converts the optical irradiation to electrical current which can be processed or recorded electronically. Many kinds of detector amplifiers are available to transform the photocurrent into reading of radiation power. Transimpedance electrometer circuits using operation amplifiers are generally adopted for interfacing the detectors. A number of studies on the construction of electrometers have been reported in the literature. In the case of $pn$ junction silicon photodetectors for measuring visible and near-infrared radiation, the maximum linear photocurrent can be up to several milliamperes when the detector is unbiased. This corresponds to a linearity of responsivity up to ten orders of magnitude. It is usually preferable for the radiometer to cover the measurement of light intensity over a multidecade range. Particularly, in the situation of long-term recording of a wide-range light signal having a fine-structured variation in each decade range, a quasilinear radiometer capable of providing a single output for representing the full range signals with a linear relation would be highly useful.

In order to have the capability of wide-range measurement, a radiometer generally is designed with range switching. Mechanical switches for the selection of ranges are usually provided in radiometers. Some commercial radiometers also include reed switches in the circuit for automatic ranging. However, the problems of leakage and noise coupling in the mechanical contact switch limit the available ranges of a radiometer. Another scheme for wide-range coverage is the use of a logarithmic electrometer to interface with photodetector. It permits the conversion of photocurrent into a decibel-represented signal without switching. However, a complicated circuit is inevitable to minimize thermal drift of the circuit accuracy. A decibel-scaled signal, as compared to the linear signal, may also be the lack of resolution in a specified range. Especially, the common methods of reducing the signal bandwidth for eliminating background noise are difficult to apply in a logarithmic converter.

In a previous article, we described an electrometer circuit implemented with complementary metal–oxide–semiconductor (CMOS) bilateral switches. It provides a quasilinear output for the measurement of dc current over eight decade ranges. It has been used successfully with $p-i-n$ photodiodes in the measurement of slowly varying light signals. In this report, an improved modification on the electrometer circuit to form a wide-range radiometer will be described. This radiometer combines the use of phase-sensitive detection correlated with the modulation of optical signals. It greatly reduces the signal bandwidth so that the circuit noise can be effectively eliminated. Together with automatic range switching and a voltage shifting circuit, the resultant radiometer amplifier provides a quasilinear analog output over a ten decade range. The use of standard integrated circuits and lock-in amplifiers makes the whole system low cost and it can be readily built. It was found to be extremely convenient for measuring various kinds of optical signals.

II. CIRCUIT PRINCIPLE

Figure 1 is the block diagram of the radiometer amplifier system. The light source modulated by the optical chopper at
chopping frequency $f_c$ is incident on the $p-i-n$ photodetector. The resultant root-mean-square (rms) photocurrent at the frequency $f_c$ is given by

$$I_{\text{rms}} = 0.45 \eta I_{\text{ph}},$$

where $\eta$ is the current responsivity in amperes per watt, and $I_{\text{ph}}$ the received light power of the photodetector. The factor 0.45 comes from the root-mean-square value of the fundamental component for a square-wave modulation. The photodetector is connected to a transimpedance electrometer similar to that reported in Ref. 6. This electrometer is configured to have six feedback resistors of value $R_f = 1 \text{k}\Omega - 100 \text{ M}\Omega$ that can be switched to cover six decade ranges. In order that the frequency response of the electrometer remains constant for all range selections, each resistor is wired in parallel with a capacitor $C_f$ to yield a frequency $f_{3\text{ dB}} = 1/2 \pi R_f C_f$. This 3 dB frequency defines the maximum operative frequency of the radiometer.

The output of the electrometer is amplified by the ac-coupled amplifier and demodulated by the phase-sensitive detector (PSD) that is correlated with the reference signal derived from the optical chopper. The ac-coupled amplifier provides $\times 1$, $\times 10$, and $\times 10^2$ selectable gain ranges. Each gain range is characterized by a predetermined time constant of 100 ms. The output of the dc-coupled amplifier is sensed by the automatic range controller to determine the actuation of proper range selection in the electrometer, the ac-coupled amplifier, the dc-coupled amplifier, and the voltage shifter. The voltage shifter further processes the output of the dc-coupled amplifier to give quasilinear voltage output.

Figure 2 is the circuit diagram of the electrometer, amplifiers, and voltage shifter. The op-amp U1 is configured as a current-to-voltage converter with feedback resistor $R_f$ selected via the CMOS switches Sa0-5 and Sb0-5. The dual-switching configuration\(^6\) results in good isolation between the different feedback resistors. Each feedback resistor of U1 is wired in parallel with a capacitor $C_f$ to yield a frequency $f_{3\text{ dB}} \approx 8 \text{ kHz}$. The $p-i-n$ photodetector is connected directly to the input of U1 in the unbiased mode. The leakage from the power supplies and control signals of the CMOS switches to the sensitive input of U1 was minimized by careful design of the guarding circuit around the input terminals. The output of U1 is ac coupled through a large capacitor to a general-purpose lock-in amplifier for simplicity. Since the effective signal bandwidth is significantly reduced by the phase-sensitive detection, the PSD provides a dc output voltage with very low noise. This dc voltage is fed to the dc-coupled amplifier which has $\times 1$, $\times 10$, and $\times 10^2$ selectable gain ranges. Each gain range is characterized by a predetermined time constant of 100 ms. The output of the dc-coupled amplifier is sensed by the automatic range controller to determine the actuation of proper range selection in the electrometer, the ac-coupled amplifier, the dc-coupled amplifier, and the voltage shifter. The voltage shifter further processes the output of the dc-coupled amplifier to give quasilinear voltage output.
the amplifiers U2a and U2b in series. The corner frequency of U2a and U2b was set to \(\sim 80\) kHz to yield frequency-independent responses over the operative chopper frequency of the radiometer. The voltage gain of both amplifiers is 10. The input and output of U2a and U2b are connected via the switches Sx, S6, and S7, respectively, to the input of the PSD. The PSD used in this experiment was a lock-in amplifier setting to a proper sensitivity and time constant. The output of the PSD is dc coupled to the amplifiers U3a and U3b in series. Both amplifiers have a voltage gain of 10. The switches Sy, S8, and S9 are used to select the properly amplified dc voltage to give the output voltage \(V_o\) through the voltage follower U4a. This output voltage is then fed to the summing amplifier U4b for a voltage shift. The switches Sc0–9 and the voltage ladder formed by the divider resistors \(R_d\) determine the amount of voltage shift. The adjustment of the potentiometer \(R_e\) at U4b gives a 1 V shift for every advancement of a decade range. Consequently, a quasilinear analog voltage \(V_q\) is obtained at the output of U4b.

An automatic range controller described previously\(^6\) is shown with some modification in Fig. 3. Signal voltage \(V_o\) is sensed by the comparator circuit formed by U5b, c. The upper and lower threshold voltages of the comparator are \(-0.095\) and \(-0.95\) V, respectively. Its output determines the advancement of the count in the binary up/down counter U6, which is clocked by the pulse generator U5a through switch S1. The binary data of U6 are transformed by the binary-coded decimal-to-decimal decoder U7 to give the range voltages \(Q0–Q9\). These range voltages are used to derive the driving voltages for the bilateral switches in the circuit of Fig. 2. The circuit of logic implementation for obtaining these driving voltages is shown in Fig. 4. The corresponding logic relation between these driving voltages and the switches actuated for each range is listed in Table I. Accordingly, when switch SW in Fig. 3 is at position \textit{auto}, the radiometer is automatically ranged over a ten decade range. A voltage of 0–10 V at \(V_q\) represents an input light intensity spanning over ten orders of magnitude with the quasilinear scale. That is, if the photocurrent of the detector multiplied by the gain of the PSD is written as \(I_{\text{rms}}K_{\text{PSD}}=a\times10^{-n}\) A, where \(a=0–0.95\) and integer \(n=0–9\), then \(V_q=[a+(9-n)]V\) when switch SW is at position \textit{manual}, the range can be selected by pressing the up and down push buttons.

### III. PERFORMANCE AND DISCUSSION

The radiometer amplifier, based on the general purpose wide-band op-amps CA3130 and LF351, has been built with well-designed guarding and shielding. A popular lock-in amplifier (Stanford Research System model SR 510) with a sensitivity of 1 V dc output per 100 mV rms input and a time constant of 100 ms was used for the PSD. A silicon diffused \(p-i-n\) photodiode (EG&G model SGD-040) with a responsivity of 0.5 A/W and a chopper frequency of 300 Hz were chosen for measurement of the visible light source. The adjustment of the circuit is very simple. By setting the automatic range controller in \textit{manual} mode and the input light intensity at zero, the trimmer \(R_e\) at U4b was adjusted to give a precise 1 V shift for one range change. The offset nulling trimmer VR100k at U3a was also adjusted to make \(V_o=0\). Because most of the signals were ac coupled, adjustment of this single offset nulling trimmer was sufficient for all ranges. Once the zero setting has been adjusted at room temperature, the output \(V_o\) showed an offset drift of less than 1 mV when the range was switched over the full decade ranges

![FIG. 4. Circuit of the logic implementation with U8: CD4069; U9: CD4072; U10, U11: CD4075. The circuit is powered by ±5 V.](image)

**TABLE I.** List of the logic relation between driving voltages and the switches actuated for each range.

<table>
<thead>
<tr>
<th>Range</th>
<th>Actuated switches (Driving signal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(Sa(0), Sb(0), Sc(0), Sx(0)), (Sy(0))</td>
</tr>
<tr>
<td>1</td>
<td>(Sa(1), Sb(1), Sc(1), Sx(1)), (Sy(1))</td>
</tr>
<tr>
<td>2</td>
<td>(Sa(2), Sb(2), Sc(2), Sx(2)), (Sy(2))</td>
</tr>
<tr>
<td>3</td>
<td>(Sa(3), Sb(3), Sc(3), Sx(3)), (Sy(3))</td>
</tr>
<tr>
<td>4</td>
<td>(Sa(4), Sb(4), Sc(4), Sx(4)), (Sy(4))</td>
</tr>
<tr>
<td>5</td>
<td>(Sa(5), Sb(5), Sc(5), Sx(5)), (Sy(5))</td>
</tr>
<tr>
<td>6</td>
<td>(Sa(5), Sb(5), Sc(6), Sx(6)), (Sy(6))</td>
</tr>
<tr>
<td>7</td>
<td>(Sa(5), Sb(5), Sc(7), Sx(7)), (Sy(7))</td>
</tr>
<tr>
<td>8</td>
<td>(Sa(5), Sb(5), Sc(8), Sx(8)), (Sy(8))</td>
</tr>
<tr>
<td>9</td>
<td>(Sa(5), Sb(5), Sc(9), Sx(9)), (Sy(9))</td>
</tr>
</tbody>
</table>

![FIG. 5. Oscillogram of output \(V_o\) during manual switching over the ten decade range with input radiation set to zero.](image)
for a ±5 °C temperature variation. It was found that the offset drift was not sensitive to the ambient humidity even for the most sensitive range.

The accuracy of the radiometer circuit for transforming the photocurrent $I_{\text{rms}}$ to the output voltage $V_q$ was determined by the precision of the feedback resistance and the 3 dB frequency of the corresponding range, provided that the sensitivity and phase of the PSD were accurately calibrated. The use of low tolerance resistors in amplifiers U1, U2, U3, and U4 was essential. The chopper frequency should also be much smaller than the 3 dB frequency to yield negligible frequency dependence in the amplitude and phase transfer function of the different ranges. In our experiment, the 3 dB frequency of $f_{3\text{ dB}}=8$ kHz and the chopper frequency of $f_c=300$ Hz lead to the amplitude and phase response of

$$T(f_c) = 1\left[1 + (f_c/f_{3\text{ dB}})^2\right]^{1/2} = 0.9993,$$

$$\Phi(f_c) = \tan^{-1}(f_c/f_{3\text{ dB}}) = 2.15°.$$

Amplifiers U2a and U2b have negligible effects on the amplitude and phase response because their corner frequency is much higher than 8 kHz. The resultant signal response associated with the phase-sensitive detection is then $T(f_c)\cos[\Phi(f_c)]=0.9986$. The analysis showed that an accuracy within ±2% over the full decade ranges was attainable when 1% tolerance resistors were used. Nevertheless, the overall linearity and accuracy of the radiometer depend on the photodetector itself. An ultimate calibration to the detector responsivity is required for achieving accurate optical reading.

The radiometer amplifier has been used extensively for optical measurements in our laboratory. Figure 5 is an oscillogram of the output $V_q$ for zero input radiation when the radiometer was switched manually over the full decade ranges. Figure 6 shows a typical plot of the emission spectrum in a gas discharge. Several emission lines have been recorded in a single wavelength scan even though the line intensities covered the range over six orders of magnitude. The feature of quasilinear representation resulted in the spectral plot whose line shape can be observed conveniently without the problem of saturation to the radiometer at high input radiation. There were spikes at the boundary of the range switching. This was a consequence of circuit switching in the amplifiers and can be easily identified.

In conclusion, a quasilinear optical radiometer with correlated phase-sensitive detection has been shown to have high performance over a ten decade range of input radiation. The combination of automatic range selection and voltage shifter circuits in the electrometer amplifier with the scheme of phase-sensitive detection provides a low-noise quasilinear analog output. It can be directly applied to various kinds of photodetectors, for example, photomultiplier tubes and pyroelectric detectors. The use of popular integrated circuits and lock-in amplifiers makes this radiometer design attractive for general-purpose optical measurements.

ACKNOWLEDGMENT

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