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A linear optical coupler for cryogenic detectors

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Abstract

We present an improved version of a linear low-noise optical coupler having differential input and capable of driving a twisted cable to long distances, avoiding ground loops and electromagnetic interference. Owing to device optimization, this circuit version is able to be fast. Its frequency bandwidth is about 900 kHz, more than ten times larger than our previous implementation. The optical coupler presented is therefore suitable to be used with most of the applications with cryogenic detectors.

Keywords: Analog optocoupler; Optical link; Electromagnetic interference reduction

1. Introduction

In experiments where the frequency bandwidth of the signals extends down to low frequencies it becomes very important to be able to avoid ground loops and electromagnetic interference, EMI. The presence of ground loops, due to the main power supply, can be a problem not only for what concerns the signal acquisition, but also for the trigger, when the trigger threshold must be as low as possible, as it is the case, for instance, for the dark matter study [1]. An analog optical coupling between the front-end readout and the acquisition system often allows to minimize this kind of noise, by breaking the interconnecting loop.

The optical coupling can be realized following two approaches: the use of optical fiber-based systems and the photodiode–LED–photodiode combination. In the first case very fast links can be implemented with solid-state laser [2]. Unfortunately, the dynamic range obtainable is not very large, of the order of 10 bits at most. With the photodiode–LED–photodiode combination, the subject of this contribution, we were able to obtain instead very low-noise and large-dynamic range, bigger than 20 bits. Up to now a limitation to this approach was given by the response speed. The present version of the optical coupler overwhelms also this limitation, thus matching the requirements of most of the present applications with low-temperature detectors.

2. A brief description of the analog optical coupler

The schematic circuit of the optical coupler, OPC, presented is very similar to the one in Ref. [3], which is an improved version of a first implementation [4]. The principle of operation of an analog OPC based on the photodiode–LED–photodiode combination is quite simple. One LED and two well-matched photodiodes, which share the light emitted from the LED, compose an integrated circuit. With the LED and one photodiode a feedback loop can be formed which forces the

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photocurrent into the photodiode to be proportional only to the input signal, irrespective of the LED working operation. This photocurrent is mirrored, with a very high accuracy, in the output matched photodiode. The input signal is then available at the output, which, as such, does not need to have the same ground reference of the input circuit.

Our approach to the realization of the OPC was aimed to obtain a high linear and low-noise system. We succeeded in this by adopting a circuit, which includes special features, where a pair of photodiode–LED–photodiode chips operate in class AB, minimizing the bias current which flows into the photodiodes, responsible for the input-shot noise, that, in the commercial circuits, is the limiting factor for achieving large-dynamic ranges. The simplified scheme of the OPC is shown in Fig. 1. The input of the OPC is differential. The class AB operation refers to the way the two chips are biased, with very low current induced by the voltage supplies $\pm V_{REF}$. The voltage V_{ACT} is an active ground that generates a signal in opposition to the input signal, allowing to double the dynamic at the operational amplifier, OA, output, V_A [3]. This in turn permits to use a value for the resistors R which is $\frac{1}{2}$ of what should be used in the case V_{ACT} were not present, with a reduction of input noise of a factor close to two. The arrangement is such that the current delivered from the input signal flows only into one photodiode at a time, depending on its sign. The implemented circuit has an additional output, not indicated in the figure, which behaves as an active ground reference. This active ground and the output signal allow to drive a twisted cable to long distances, obtaining complete shielding from EMI.

In the previous version of the OPC we used the optical coupler IL300 by Siemens, with a bolometric detector [5]. The IL300 has a transfer function limited to about 200 kHz. The OPC realized has a frequency bandwidth of about 70 kHz, fully adequate for the bolometric detector applications.

With the aim to realize a device with more general specifications, we tried to look for an optical coupler with enhanced characteristics. We succeeded in this search with the HCNR201 by Hewlett Packard, which is a photodiode–LED–photodiode chip with a frequency response closed

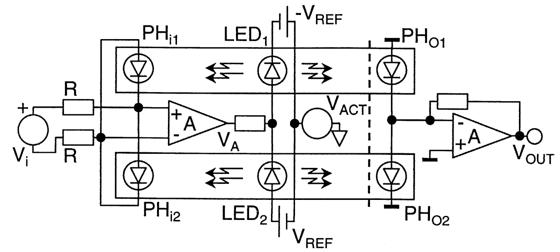

Fig. 1. The very simplified schematic diagram of the analog optical coupler realized.

to 1.5 MHz, much faster than the IL300. With this device we have realized a circuit based on the one described in Ref. [3], but with different OA needed to realize the structure, the Elantec EL2444. The EL2444 is a quad-high-speed OA having a bipolar pair as input transistors. With the new arrangement the OPC becomes very fast, as can be observed in the photograph of Fig. 2, showing the OPC response to a step voltage, when the bias current for the photodiodes is only about 100 nA. The rise time is about 400 ns, corresponding to a bandwidth of 900 kHz. The total harmonic distortion (THD) has reached negligible levels, as can be seen in Table 1, where some measurements are shown for different values of the photodiode bias current. A supply voltage of ± 14 V has been applied to the circuit and a sinusoid of 1, 20 and 30 kHz with 20 Vpp was the test signal. For the range of input signals amplitude extending up to 20 Vpp the maximum nonlinear integral error is 0.15%, and the power dissipation of the circuit is about 1.1 W, limited by the current absorption of the EL2444 used. In this condition, the temperature of operation of the OAs is about 60°C. The transfer ratio of the photodiode current to the LED current was measured to be about 0.5% down to 100 nA photodiode currents.

Fig. 3 shows the series noise at the OPC input measured in two different conditions in the frequency range 1 Hz–10 kHz. The photodiodes have been operated at 100 nA in both cases. The two measurements differ for the OAs used in the circuit: the EL2444 or the quad OA LM6144 (National). In the first case, the noise amplitude coincides with the behavior expected from the parallel input noise of the EL2444, that limits the performance to about 1 $\mu V/\sqrt{Hz}$ at 1 Hz, and 140 $nV/\sqrt{Hz}$ for the white

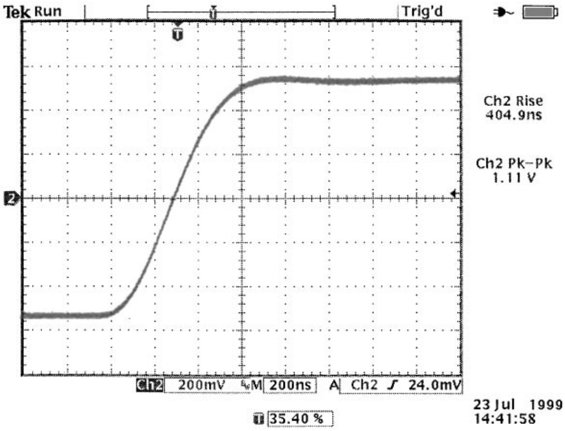

Fig. 2. A Tek photograph of the step response of the optocoupler. The horizontal scale is 0.2 μs/div, the vertical scale is 0.2 V/div.

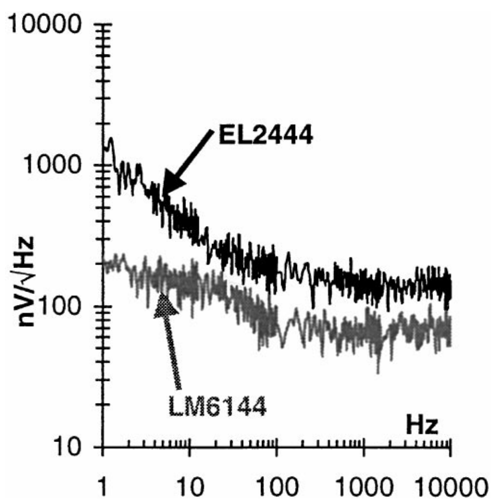

Fig. 3. Noise of the optocoupler when the photodiodes are operated at 100 nA, the noise floor is dominated by the Operational Amplifiers used, EL2444 (upper line) and LM6144 (lower line).

component. In the second case, to enhance the properties of the HCNR201, an LM6144 was used, because it has a lower parallel noise. As shown in Fig. 3, the noise reduces to 200 $nV/\sqrt{Hz}$ at 1 Hz and 60 $nV/\sqrt{Hz}$ at high frequencies. But the frequency bandwidth of the circuit with the LM6144 is about 160 kHz (2.1 μs of rise time), because they are slower than the EL2444, and therefore do not permit to exploit the characteristic of the HCNR201 fully. Power dissipation also reduces to about 0.1 W in the latter case.

Table 1
Total harmonic distorsion (THD) at different DC photodiode bias currents. The THD has been measured for 20 Vpp sinusoidal output voltage

I_{PH} (μA)	THD at 1 kHz (%)	THD at 10 kHz (%)	TDH at 30 kHz (%)
0.1	0.086	0.075	0.070
0.29	0.083	0.070	0.066
1.06	0.060	0.080	0.116

The properties of the OPC are also evident in Fig. 3. As can be seen in the noise spectra no peak appears at 50 Hz, thus demonstrating the absence of interference from main supply. The noise was measured by making the OPC drive a twin coaxial cable, RG108: a differential amplifier converts the twisted signal of the twin cable to a single ended signal, which is then sent to the spectrum analyzer.

3. Conclusions

An analog optical coupler based on a previous low-noise design has been optimized in terms of speed of response by device optimization. The frequency bandwidth of the new version is about 900 kHz, with a rise time of 400 ns, more than ten times faster than any previously realized. The total harmonic distortion measured at 20 Vpp for the output signal is about 0.1%, while the non-linear integral error is 0.15%. This circuit is now adequate to be used with most cryogenic detectors.

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