Optoelectronic Signal Transmission by Diffuse Radiations: Design and Performances.

Optoelektronische Signalübertragung mit einer 300-mW-LED.

Abstract

In a variety of short-distance signal transmission applications, an optoelectronic link based simply on direct and/or diffuse radiation is attractive because of immunity to e.m. disturbances, compactness of both transmitter and receiver, and easiness installation. We discuss here the design of an optoelectronic transceiver, based on a 300 mW LED array as the source and on cheap, large-area photodiodes as the detector, which can operate by diffusion up to several tens of meter with some 100kHz bandwidth. No collimation optics is required for the transceiver, and operation is secured by either direct-sight propagation or diffusion at walls and ceiling.

1. Introduction

Optoelectronic data transmission by direct or diffuse radiation, i.e., with open propagation not confined in an optical cable, are an alternative interesting approach for short-distance, medium speed applications. While preserving a high level of EMI immunity, comparable to that of fiber-optics, they have the further advantages of requiring no cable installation, can be used as mobile links, and offer a substantial cost saving, also because of the cheaper components required. Typical applications of the diffuse optoelectronic link are, e.g.: the interconnection of a central unit to several peripherals (in computer and control systems) through the diffusion of light on the ceiling and the walls of a large room, and the in-sight interconnection between buildings to dispense for dangling cables or long installation works. Another application, involving the mobility of the link, is that of the telephone set, where the cable connection between set and receiver is eliminated.

2. Design of transmitter and receiver

The link has been designed around low-cost components, such as the Siemens LED LD271, emitting 16 mW nominal power at $\lambda = 950$ nm ($\Delta \lambda = 50$ nm), and the Siemens photodiode SFH205, having an active area of 7.5 mm$^2$ and internal coloured filter ($\Delta \lambda = 150$ nm) matched to the LED spectrum. By assembling 24 LEDs in a 30x20 mm$^2$ array, a radiant power of 330 mW was obtained at the nominal 100 mA dc average current per LED. The current was modulated from 10 to 190 mA resulting in a 2x300 mW peak-to-peak power swing of the modulated radiation emitted by the source. With these values, distortion of the transmitted sine-wave was within 5%. The high frequency cutoff of the LEDs was measured to be 500 kHz as from device specifications—which means that a 1 Mbit/s could be accommodated with some pre- or post-emphasis. The drive circuit is shown in fig. 1: two BFY56s feed a 12-LED series each, and provision is made to equalize the load currents (trimmer P1) and quiescent work point (trimmer P2).

The receiver was designed to ensure three basic requirements: i) a good low-noise performance; ii) immunity to e.m. interference; iii) capability of handling a large d.c. stray illumination without saturation. Starting from the well-known cold-resistance approach to point i), a FET-input LF351 operational amplifier was used to collect the photodiode current, with low noise and high bandwidth, in the virtual ground at the inverting input of the op-amp. Using a feedback resistance of 82k$\Omega$, the 3-dB bandwidth was 500kHz and a noise-equivalent-current of 1pA/√Hz was measured (instead of a theoretical value of 0.5 pA/√Hz) as due to the amplifier; the dark current 0.07 μA of the photodiodes added a contribution just measurable, of 0.5 pA/√Hz. While the signals down to a few nA were detectable, the d.c. current of the photodiodes at high levels of ambient illumination, e.g. 2000 lux, could be of the order of 100 μA.

Thus, an a.c. input coupling was mandatory to avoid saturation, and it was implemented with an inductor-capacitor combination (fig. 2) to terminate the photodiode d.c. circuit without adding resistive components and their accompanying noise. To improve the immunity to interference, a cancellation technique was devised, see fig. 2.

A dummy wiring running close to the photodiodes and miming their wiring geometry, was used to collect the same electric field disturbance. It was then connected to the non-inverting op amp input so as to be subtracted to the photodiode signal output. By adjusting the trimmer PA, a near perfect cancellation was achieved, i.e. a reduction of $\approx 30$ dB of EMI disturbances. This was actually necessary because...
the receiver could work down to 100 µV output signal with good S/N ratio, while EMI was much larger than noise in ordinary circumstances. The signal from output \( V_s \) (fig. 2) was handled in conventional way: we added an AGC stage to complete the receiver for analog data and baseband transmissions, and also tested a PSK scheme with 200 kHz carrier and 50 kb/s bit rate for digital data transmission.

3. Performances

Measurements of signal amplitude and signal-to-noise ratio \( S/N \) were performed in a normal laboratory environment, both for diffuse and direct-sight operating modes. The ceiling, at 3.5 m height, was illuminating pointed the transmitter upward in the diffuse mode, and the receiver was oriented loosely toward it; no collimation optics was used in the diffuse nor direct-sight mode.

Since the emission is nearly isotropic in angle, i.e. like a Lambert's source, the attenuation introduced by propagation is calculated as \( \delta A_D/n L^2 \) where \( L \) is the average distance between transmitter and receiver, \( A_D \) is the receiver photodiode area and \( \delta \) is the diffusivity loss.

It follows that the signal current of the photodiodes is \( S = \sigma P_t \delta A_D/n \lambda L^2 \), where \( \sigma = 660 \text{ mV/W} \) is the spectral sensitivity at 950 nm and \( P_r = 210 \text{ mW} \) is the rms value of ac transmitted power. The noise is dominated by the shot-noise contribution of stray illumination: \( N = (2e \sigma^* E) / \sqrt{h} \) where \( \sigma^* = 50 \text{ nA/lux} \) is the responsivity to an illumination \( E \) (lux) supplied by a 2800 K source (neon tube lamps and natural illumination have a \( \sigma^* \) value much alike).

By using a bandwidth \( B = 100 \text{ kHz} \), an \( A_D = 6 \times 7.5 \text{ mm}^2 = 45 \text{ mm}^2 \) photodiode area, and assuming \( \delta = 0.5 \), we find from the above expressions a signal-to-noise ratio \( S/N = (31 \text{ mV/L}^2 \text{ (1000 lux/E)})^n \), as a function of distance \( L(m) \) and ambient illumination \( E \) (lux) for our optoelectronic diffuse link. Experimentally, while the trend of \( S/N \) with \( L \), \( E \) and \( B \) was well matched by measured data, the actual \( S/N \) values were slightly less than predicted because the noise \( N \) was 2...4 dB larger than expected by shot-noise limit. In normal illumination conditions (\( E = 200...500 \text{ lux} \)) we obtained working distances of 20 m in diffuse transmission, with 50 kHz bandwidth and the necessary signal to noise ratio \( S/N = 15 \text{ dB} \) to ensure a low \((< 10^{-6}) \) error probability.

To solve quickly problems of performance evaluation, we report the double-diagram of fig. 3, which allows to obtain signal \( S \) as a function of transmitted power \( P_t \) and distance \( L \), and noise \( N \) as a function of ambient illumination \( E \) and bandwidth \( B \). Once the signal (open point in fig. 3) and the noise (full point in fig. 3) have been determined, their vertical distance yields the \( S/N \) ratio. The diagram assumes a sensitive area of the photodiodes \( A = 50 \text{ mm}^2 \) and a \( \sigma^* = 50 \text{ nA/lux} \). For a different area, \( A = kA_D \) read the S-scale multiplied by \( k \) and the N scale multiplied by \( k^2 \); for a different \( \sigma^* = h \cdot 50 \text{ nA/lux} \), multiply the E-scale by \( h \). Finally, the diffusivity loss \( \delta \) can be accounted for by entering the diagram with \( \delta P_t \) instead of \( P_t \).

The performance of the optoelectronic link was obviously improved when the transmitter and the receiver were faced in direct sight: a typical gain of \( 1/\delta = 2...4 \) in signal and \( 1/\sqrt{\delta} \) in distance was observed, the other parameters being unchanged. Clearly, a significant extension of distance \( L \) can be gained by increasing the received power through collimation of the transmitted beam, or by a collecting objective in front of the photodiodes. The gain is given by the ratio of the solid angle of transmission (reception) to that of emission (detection). However, a practical limit to this sort of antenna-gain is set by the criticality of alignment which is time-consuming to perform and unreliable when the transmission or reception angles have been reduced down to a few degrees. For immobile links, the trade-off between alignment (and associated mechanical requirements) and gain is, in our opinion, at an angular aperture of \( 2 \times 10^\circ \) both for transmission and reception, which amounts to increase the equivalent power \( P_t \) (in fig. 3) of a factor 1000 with respect to the Lambert's source or detector. A check was performed by using a single LED (10 mW rms) and a single photodiode with plano-convex objectives (\( R = 20 \text{ mm} \) and 100 mm) to cover a distance \( L = 50 \text{ m} \) with 20 dB - S/N at 100 kHz bandwidth.

![Fig. 2](image-url) Low-noise, EMI-cancellation receiver.

![Fig. 3](image-url) Chart for the evaluation of signal \( S \), noise \( N \), distance \( L \) from bandwidth \( B \) transmitted power \( P_t \), ambient illumination \( E \).