Experiment No. 5. Pre-Lab

LEDs and Phototransistors, Digital Optical Communications

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1.0 Light Emitting Diodes:

Light emitting diodes (LED) are used extensively in displays, remote controls and sensor systems (intruder alarms, etc. ...). You may be surprised to know that any pn diode emits light when biased, but only the LEDs are optimized to generate a lot of light and to allow this light to escape from the semiconductor. The wavelength of the emitted light is proportional to the bandgap of the semiconductor (see EECS 320) and different materials are used to generate different light colors (Table 1).

Structure	Material	Bandgap type	Peak wavelength, nm (color)	Typical performance, lm/W
Homojunction	GaAsP	Direct	650 (red)	0.15
	GaP: Zn, O	Indirect	700 (red)	0.4
	GaAsP: N	Indirect	630 (red) 585 (yellow)	1
	GaP: N	Indirect	565 (yellow-green)	2.6
	GaP	Indirect	555 (green)	0.6
	SiC	Indirect	480 (blue)	0.04
Single heterojunction	A1GaAs	Direct	650 (red)	2
Double heterojunction	A1GaAs	Direct	650 (red)	4
	A1GaP	Direct	620 (orange)	20
	A1InGaP	Direct	595 (amber)	20
	A1InGaP	Direct	570 (yellow-green)	6
	GaN	Direct	450 (blue)	0.6
Double heterojunction with transparent substrate	A1GaAs	Direct	650 (red)	8

Table 1: CHARACTERISTICS OF VISIBLE LIGHT-EMITTING DIODES (from M.G. Craford, "LEDs Challenge the Incandescents," *IEEE Circuits and Devices Magazine*, September, 1992).

A cross-section of an LED is shown in Figure 1. The small V-shape reflector behind the pn junction reflects the light emitted to the backside and therefore increases the forward light intensity. Also, a magnifying dome lens is placed in front of the diode to concentrate the emitted light in a narrow angle (typically 20-90˚) from the boresight.

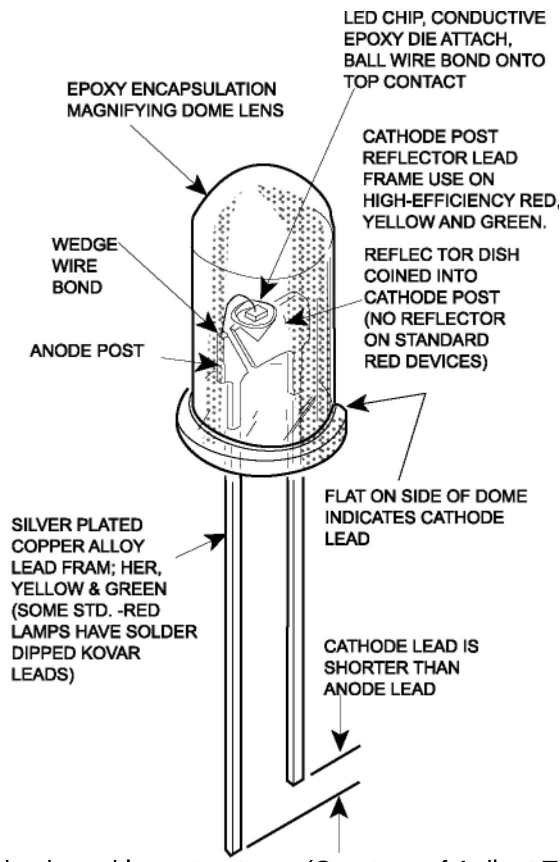

Figure 1: An LED and its domed lens structure. (Courtesy of Agilent Technologies).

One of the main most confusing notations in LED (and photometry in general) is the Lumens and Candlelight units. The basic unit of power in SI units is W (or mW). When you have radiation, the basic unit of power is W/m^2, (or mW/cm^2) and specifies the power density of light (or electromagnetic radiation) produced at a certain distance from the source. This means that if an LED produces an on-axis power density of 0.1 mW/cm^2 at a distance of 10 cm from its location, and there is a detector with a capture area of 0.2 cm^2, then the detector will capture 0.02 mW of power (Fig. 2). This is easy and intuitive and all of the wireless/RF/microwave field relies on these units.

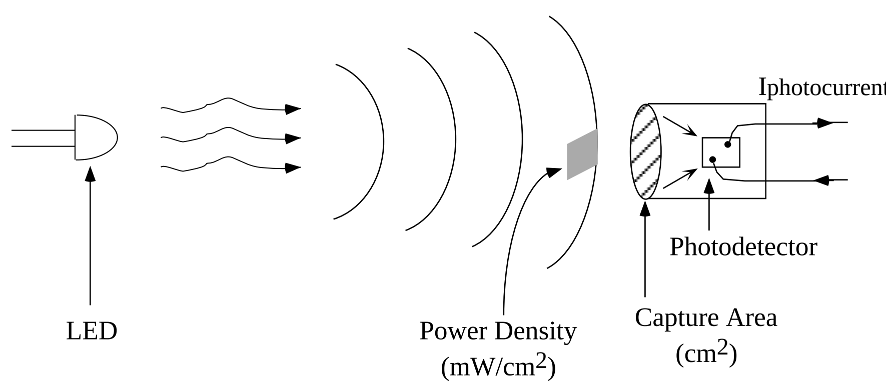

Figure 2: Schematic representation of power density and capture carea.

However, life is not that easy when the human eye is involved since its response is very sensitive to the wavelength of light (Fig. 3a). The eye is most sensitive to 555 nm (greenish/yellow colors) and has about 20 times less sensitivity to the red or blue colors. So, if two LEDs, a green/yellow and a red one, are emitting the same amount of optical power in mW (or mW/cm^2), then the green/yellow one will appear 20x brighter than the red one! Fig. 3 is called the CIE curve (Commission Internationale de L'Eclair), a French commission which has set this standard since more than 100 years.

So, rather than specifying an LED diode by the amount of optical power it produces in nice SI units such as mW (or mW/cm^2), it is specified in *Lumens* or *millicandella (mcd)* and it is the unit of power as *perceived* by the eye! Look at the specifications of the Agilent 3316 LED (red) and the Agilent 3416 LED (yellow). They both have the same rating of a minimum mcd of 20 for a 10 mA of bias current. However, the red LED must be giving around 18x more optical power to be perceived as bright as the yellow LED. Since both LEDs have the same input power, the red LED is therefore 18x more efficient in converting its input power to optical power than the yellow LED!

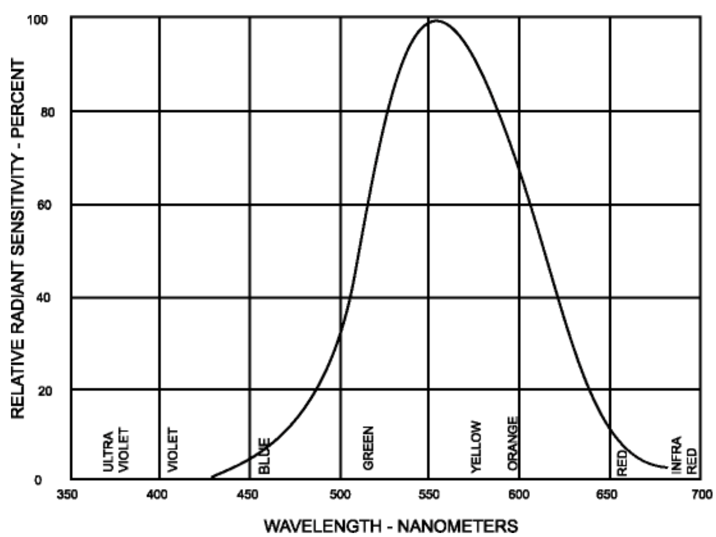

Figure 3a: The CIE curve. From *Optoelectronics*, Vaughn D. Martin, p. 12.

The Agilent3316 LED (see attached data sheet):

This LED is made of a new heterostructure material, AlGaAs, and has a very high conversion efficiency (6-8%) between the input power and the emitted light intensity (optical power). Its peak wavelength is 635 nm (red) and its spectral line width (bandwidth of emitted light) is only 40 nm. This is the reason it appears as an intense red and not a mix between red and yellow. It delivers 60 mcd (millicandella) typical at 10 mA of forward current which is a strong light for such a small amount of current. The angle between the half-power point is 35˚ and therefore it is quite directive. It is a fast LED with a capacitance of only 11 pF and a response time of 90 ns, and therefore, can be modulated up to 5 MHz for AM or FM applications.

The Agilent 3316 output light intensity is linear with applied current as shown by the graph of the relative luminous intensity vs. dc current (Fig. 3b). Actually, the light generation inside an LED is very complex and does not follow an exponential law. For a dc current of 15 mA or above, it is possible to ac modulate the current by +/- 5 mA while keeping a linear response, and therefore resulting in low distortion modulation. Since the diode resistance is around 3 Ω ($r_d = nV_T/I_{DC}, n = 2, V_T = 26mV$ and $I_{DC} = 15mA$), this means that an LED can handle ±15 mV$_{pk}$ (or 30 mV$_{ppk}$ across rd) before any appreciable distortion. This is much larger than a regular PN-junction diode.

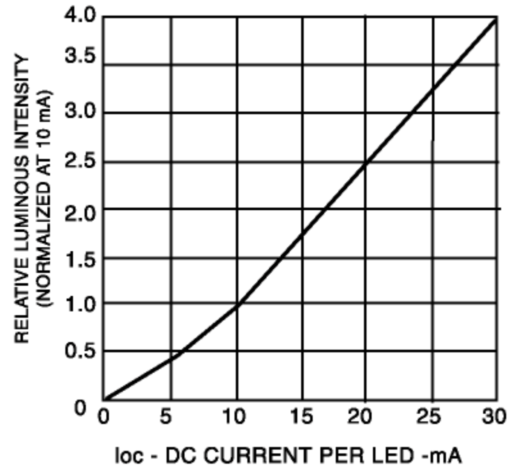

Figure 3b: Relative light intensity vs. DC input current for the Agilent 3316 LED.

2.0 Phototransistors:

A phototransistor is a transistor which is sensitive to the input light intensity. Basically, a small lens focuses the light to the base, and this light interacts with the semiconductor crystal and generates electrons (Fig. 4). The electrons are amplified by the transistor and appear as a current in the collector/emitter circuit. This current is called the "photocurrent". A phototransistor has only two leads since the base is internally left open and is at the focus of a plastic lens.

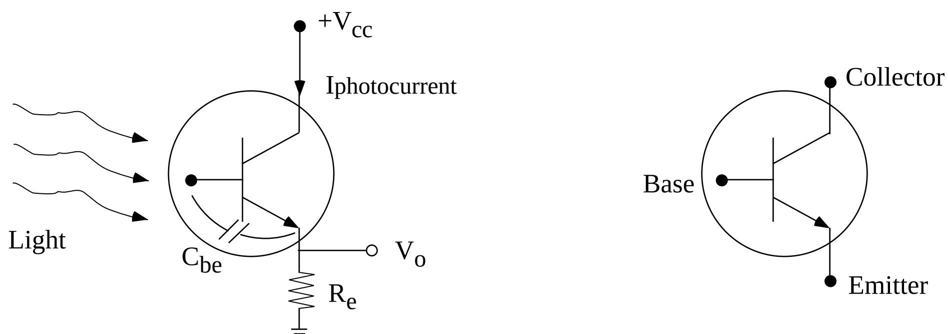

Figure 4: Schematic representation of a phototransistor. The base is generally not connected to the outside world.

The most important specification of a phototransistor is its spectral sensitivity. The Siemens BPX 81-3 is a silicon infrared phototransistor with a peak sensitivity at 860 nm (see attached data sheet). Its sensitivity drops to 60% of the peak value at 630 nm which is the wavelength of the Agilent 3316 LED. It is a directional phototransistor with a half-power sensitivity angle of 36˚ and therefore will not pick up a lot of noise from the neon lighting system on the ceiling. The photocurrent is specified in terms of Lumens (Lx) or in terms of incident power density (mW/cm^2), and is around 0.5 mA for an incident power density of 0.4 mW/cm^2. Another important spec. is the "dark current", and as its name indicates, it is the current which flows in the collector-emitter circuit for no input light. This is basically the internally generated noise of the phototransistor and is the limiting factor to the sensitivity of the photoreceiver system.

The speed of the phototransistor is limited by the base-to-emitter (C_{be}) capacitance and is specified in terms of the risetime of the device. Since C_{be} interacts mainly with the load resistor (R_e), the risetime is linearly dependent on R_e. For R_e= 1 KΩ the risetime is 6 µs, meaning that it can follow accurately a 100 KHz square-wave modulation. Phototransistors are not fast devices, and for a faster response, it is best to use a *photodiode*. A photodiode is basically the input section of the phototransistor (collector-to-base section) and does not have an emitter and therefore, does not suffer from the C_{be} effect. However, it produces 40-200x less photocurrent and therefore must be always followed by a differential amplifier. It is possible to build photodiode-based optical receivers with response times of sub-ns and these systems can detect GHz modulation speeds. These detectors are used in high-speed fiber optic systems.

3.0 Phototransistors and Square-Law Detection:

The photodetection process is inherently a non-linear process since the output current, I, is proportional to input power (or light intensity), P, and therefore to the input voltage squared.

$I = kP$ proportional to V^2

where k is the detector responsivity and has units of A/W. In the pre-lab, you will calculate k for the Siemens BPX 81-3 phototransistor.

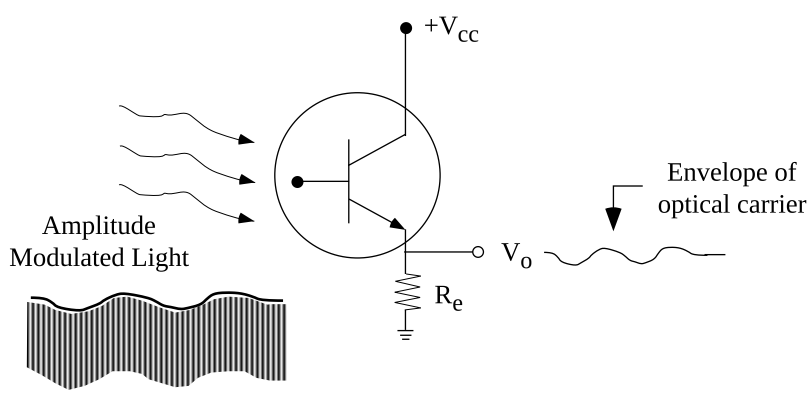

Figure 5: A phototransistor as an AM demodulator (envelope detector).

Since the detection process follows the square-law rule, it automatically demodulates any amplitude modulation on the optical carrier, just as the diode AM demodulator! The output voltage across R_e is therefore the demodulated signal (Fig. 5). If there is no amplitude modulation on the optical carrier, then the output voltage is a DC voltage and the phototransistor is acting as a square-law power meter (output dc voltage is proportional to the input power (or light intensity).

With phototransistors, it is easy to explain the AM detection process using the time-constant approach. Remember that the phototransistor is a slow device and can only respond to changing signals of 1 MHz maximum. This means that it will surely not respond to the instantaneous optical signal (at 300 THz) and only to its envelope which is changing at KHz frequencies. Well, here it is, you have an *envelope detector* and therefore an AM detector!

4.0 Digital Optical Communications:

The Although you will build a simple AM photonic link in Experiment #5 and use it to detect music in the lab with a bandwidth of 20 KHz, you should know that the backbone of the terrestrial telecommunication system is based on this simple idea. The modern digital telephone system works this way (Fig. 6):

1. Take several thousand users at the local switching office and digitize their voice (analog/digital converters) at a sampling rate of 6 KHz and an 8-bit resolution. This means that a single user generates a data stream of 48 Kbit/second (with no compression) and around 16 Kbit/second with compression.
2. Put several of these users on the same line. If you can transmit 1.0 Gbit/second, this means that every second you can put around 60,000 users on the same line! Actually, you

need to put timing signals on the line and also the destination information. So, let us say that you can put 30,000 users on the line. The unit that does this is called a "multiplexer".

3. Modulate a laser diode (equivalent to the LED) digitally with the 1 Gbit/second information and put the output light of the laser diode in a fiber-optic cable. This is pure digital AM with "1"s and "0"s.
4. Run the fiber optic cable from NY to Chicago making sure to amplify the signal every 20 or so miles (since the light is attenuated a bit in the fiber-optic cable). The amplifiers are called "repeaters".
5. Use a photodiode (similar to the phototransistor) at the receive end and take the 1 Gbit/second information and divide it down into the 30,000 different users and the destination information. This is called a "demultiplexer".
6. Send each of the 30,000 different users to their respective destinations. This is called a "switching network" or a "routing network".
7. Just before it arrives to the final destination, decompress the signal and pass it by a digital to analog converter. You now have a connection between NY and Chicago!
8. And, imagine that this is all done is about one second after you finish dialing a number!

P.S: If you are sending internet information, then you do not need the A/D and D/A converters at both ends.

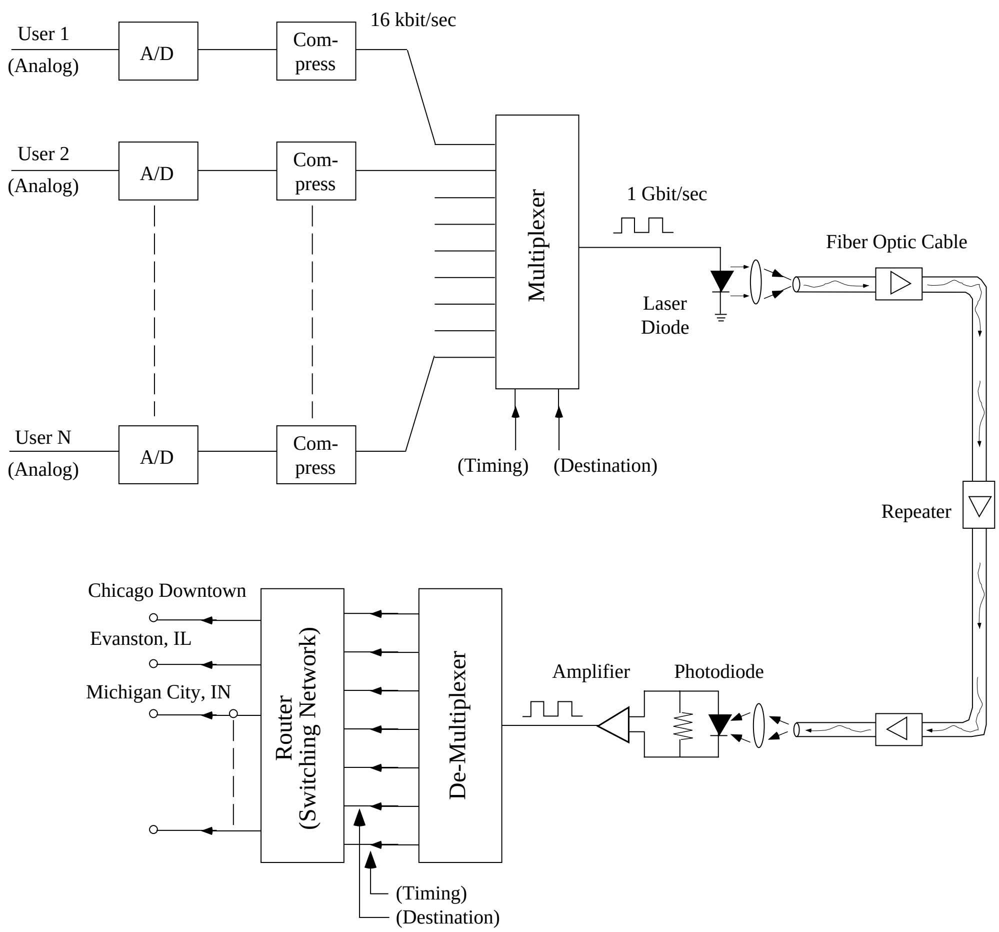

Figure 6: The optical digital telephone system