Introducing Optical Concepts in Electrical Engineering

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Abstract:

The expansion in the fields of optical engineering and optoelectronics has made it essential to introduce optical engineering concepts into undergraduate courses and curricula. Because of limits on the number of course requirements for the BS degree, it is not clear how these topics should be introduced without replacing some of the traditional requirements. This paper demonstrates how optical engineering concepts can be easily presented as an integral part of electrical engineering subjects, with a minimal amount of replacement, while enhancing the depth and understanding of both fields. Courses such as linear signals and systems, electricity and magnetism, and electronics which traditionally represent the core requirements of the undergraduate electrical engineering curriculum, have subjects that have direct correlations with optical engineering concepts. The major changes that are needed are the creation of textbooks that contain concepts and examples in areas of both optical and electrical engineering and some relearning and familiarization on the part of instructors. This approach allows for a fresh look at courses being offered in electrical engineering, while providing the necessary background in optical engineering for students.

Introduction

The narrow focus of many engineering curricula has resulted in engineers with very limited engineering ability, who are afraid to explore possibilities beyond the basic topics that they have learned in their undergraduate programs. Generally, there are several limitations that prevent engineering students from venturing beyond the required courses. These include pressure from administrators, at least in public institutions, to reduce the number of required credit hours to allow fast turnover, eagerness on the part of the students to graduate as soon as possible to participate in a booming job market, the unavailability of textbooks with a wider point of view, and finally, the limited expertise of instructors.

A typical electrical engineering curriculum starts with circuits and systems and leads to courses in communications and signal processing followed by two or three courses in electronics. Meanwhile, there are one or two courses in electromagnetics, antennas, control theory, transmission lines, and power, which are expected to prepare students for the BS degree in electrical engineering. Throughout these courses, there are many overlaps so that the topics in one course provide the foundation or essential knowledge for the understanding of another course. For example, Fourier analysis learned in linear systems is heavily used in communications and control theory, and topics that are learned in electricity and magnetism are used in electronics. All these, including the mathematical details used to explain them, circle around the nature of electric currents, i.e. the displacement or acceleration of electrons in wires or space. This omits a large portion of the universe which consists of particles that do not carry charge. These particles, like photons, are increasingly being used for optical computation, communications, and signal processing[1].

Optical communications and signal processing have expanded continuously since the early eighties. Today, almost all telephone communication is optical and it is hard to find any electrical systems that are not at least partially optical. Although no one predicts that optical systems will replace electrical systems, it is clear that most systems will be a combination of optical and electrical. Therefore, it is important to include optical concepts in electrical engineering courses. This will certainly turn out better prepared graduates who can include optical approaches in their designs and deal with the inevitable optical expansion in electrical engineering.

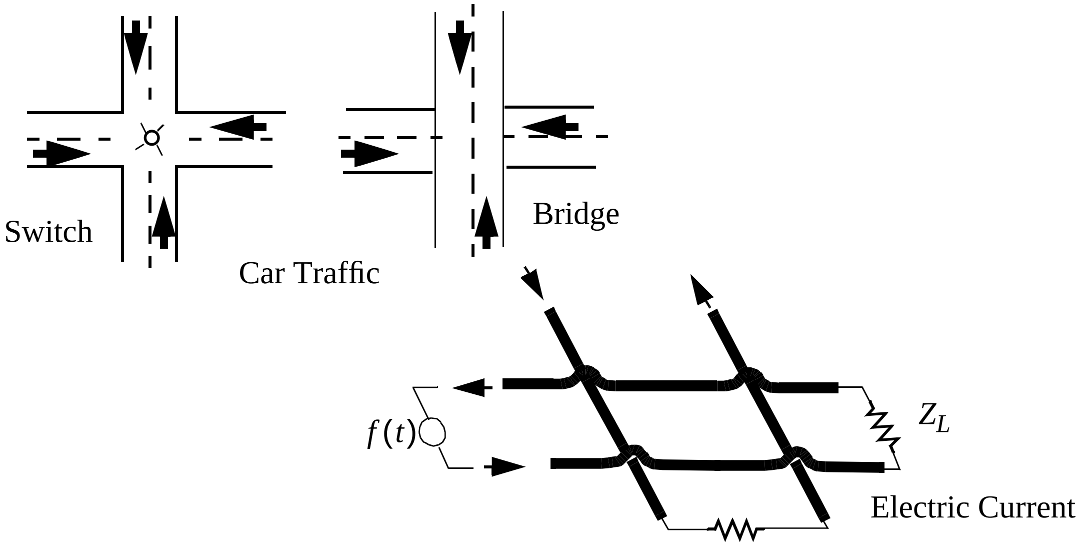
Basic approaches

In what follows, similarities and overlaps in electrical and optical engineering are presented and the ways that each of these fields can be enhanced if taught simultaneously are demonstrated with examples from both areas.

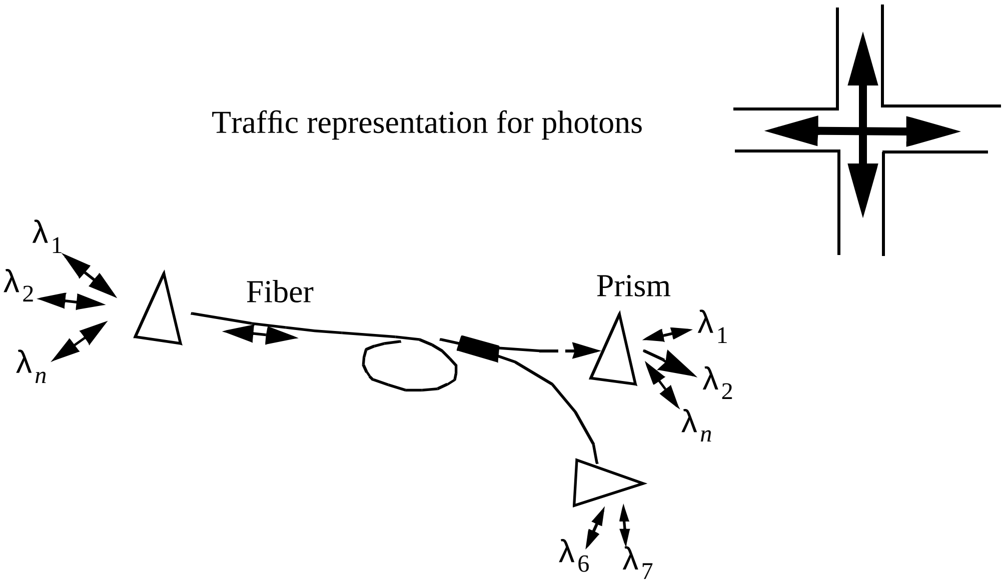
To present optical circuits in basic circuit theory, one can compare the properties of electrons to photons. Nature consists basically of two categories of particles which are known as fermions, particles like electrons who carry charge and spin of *1/2*, and bosons, particles like photons which are neutral with integer spins.[2]. Traditional electrical engineering courses consist of approaches that deal with electrons alone. Electrons carry charge and interact strongly with other electrons. As a result, the electronic interconnects need to be insulated from each other and two wires are needed to send an electric signal back and forth. On the other hand, photons of light do not interact. This allows a fiber or waveguide to be used for sending many signals in both directions and a simple prism can do a Fourier transform and its inverse simultaneously.

Consider a typical automobile traffic system shown in Fig(1a). In the simplest case, there are two possible ways that a safe crossroads for two way traffic can be constructed. You can have a switch at the crossroads, i.e. a traffic light, or have one road cross over the other one. Furthermore, you need to have two lines in each direction for the oppositely moving traffic. This is the same required condition for electronic circuits. That is, two conductive lines are needed to carry the electric current in opposite directions and at the cross-section there must be a switch or insulation between the electric lines to prevent a short circuit. More wires are needed if more than one electrical signal must go both ways simultaneously.

To accomplish the same task by optics, only one line (fiber optic or waveguide) is needed to carry optical signals in both directions and at the crossing there is no need for a switch. The two optical signals can pass through each other with no interaction. In principle, one can use a single fiber to transfer many optical signals simultaneously in both directions[3]. This is a very important advantage which reduces the number of optical interconnects and allows much simpler optical circuits. A possible form of multi-channel fiber optic communication is shown in Fig(1b).



Fig(1a). A typical automobile traffic intersection, top, is compared with a simple electronic circuit.



Fig(1b). An optical circuit is shown which consists of a fiber optic, optical coupler and three prisms. On top, a crossing point for a light wave is shown to demonstrate the lack of interaction between the photons.

In Fig(1a), a pair of wires is used to transmit a time varying signal. This is compared with Fig(1b), in which a fiber is used to combine several signals at different frequencies, i.e. inverse Fourier transforms to a time varying function $f(t)$ and then Fourier transforms back to $F(\omega)$ by a prism. It is a major limitation, if at the time electrical transmission through wiring is taught, not to refer to the fact that many signals can be transmitted simultaneously on a fiber. Furthermore, a prism is the best example for Fourier transform, that is, transforming the amplitude function into a spectral function.

In basic circuit analysis the output voltage and current are related to the input current and voltage by an (ABCD) matrix, shown in Fig(2). Similarly, using optical ray tracing in an optical system, the radius and the angle of the output ray of an optical system is related to the radius and angle of the incident ray and follows the same algebraic manipulation[4].

The impulse response method in electronic systems is used to find the response to any arbitrary function. That is:

$$f_o(t) = f_i(t) \quad h(t) \qquad \text{(EQ 1)}$$

where $h(t)$ is the impulse response. Of course (EQ 1) also can be written as:

$$F_o(\omega) = F_i(\omega) \quad H(\omega) \qquad \text{(EQ 2)}$$

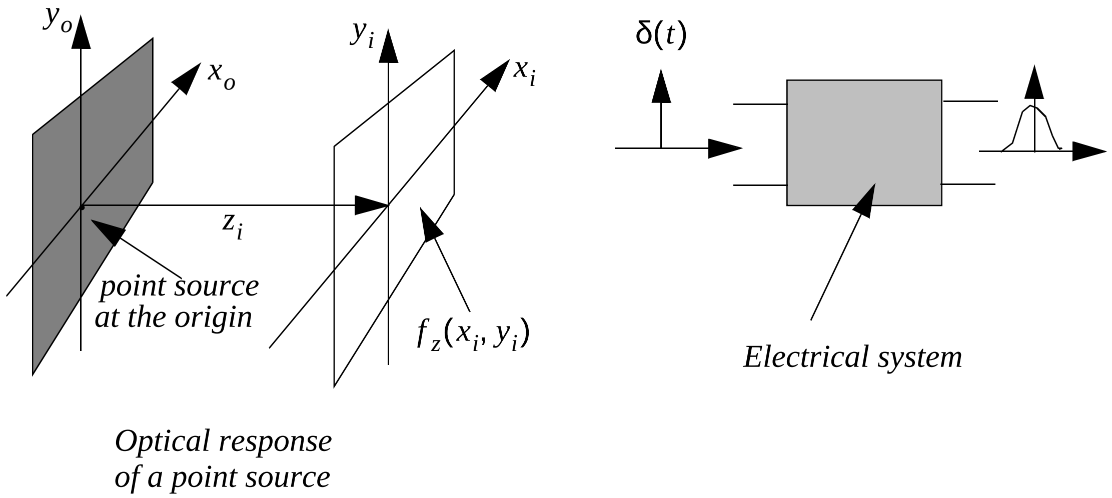
It is easy to show that the image of a two dimensional object $O(x_o, y_o)$ can be found by a convolution operation. That is:

$$u(x_i, y_i) = O(x_o, y_o) \quad f_z(x_i, y_i) \qquad \text{(EQ 3)}$$

where

$$f_z(x_i, y_i) = \frac{p}{j\lambda z_i}\exp\left[jk\left(z_i + \frac{x_i^2 + y_i^2}{2z_i}\right)\right]$$

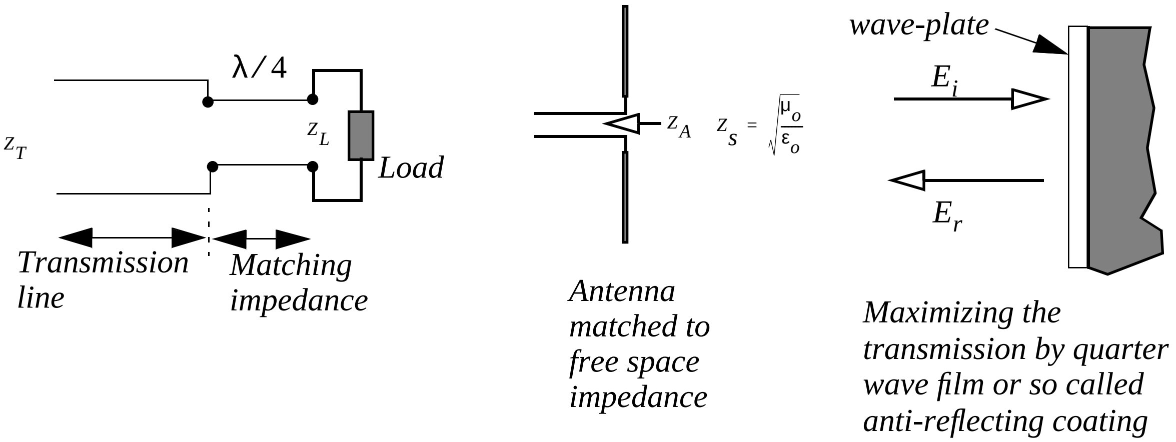
is of the same form as the approximation obtained by binomial expansion of r in the expression e^{jkr}/r for a point source located at the origin. For this reason $f_z(x_i, y_i)$ is called the point source transfer function. This concept should be compared with the concept of impulse function[5] in electronic devices, shown in Fig(3).



Fig(3). The impulse response of a circuit on right is compared with the image of on a screen a point light source

In transmission lines, one is always concerned with matching the line impedance to the load in order to prevent power reflection. A similar concern arises when an antenna impedance needs to be matched to free space impedance for maximum transmission. The best example to help understanding in both fields is the reflection of light in a normal incident from a dielectric medium, such as glass[6,7], demonstrated in Fig(4).

The operation of diodes and transistors in electronic circuit analysis is determined by their load line in a circuit. Fig(5) shows the graphical analysis of a diode circuit on the right. Optical transmission through a ferroelectric slab with two highly reflecting surfaces is shown on the left of Fig(5). The transmission as a function nkd is an Airy function and the output intensity can be modulated by an external applied field[8] ΔE. In this figure, n is the index of the refraction of the ferroelectric medium which is electric field dependent, k is the wave vector and d is the dielectric thickness. As demonstrated in Fig(5), the similarities between the optical and electrical systems are overwhelming and combining these two fields at a very early stage of electrical engineering courses and curricula will result in many advantages.



Transmission line

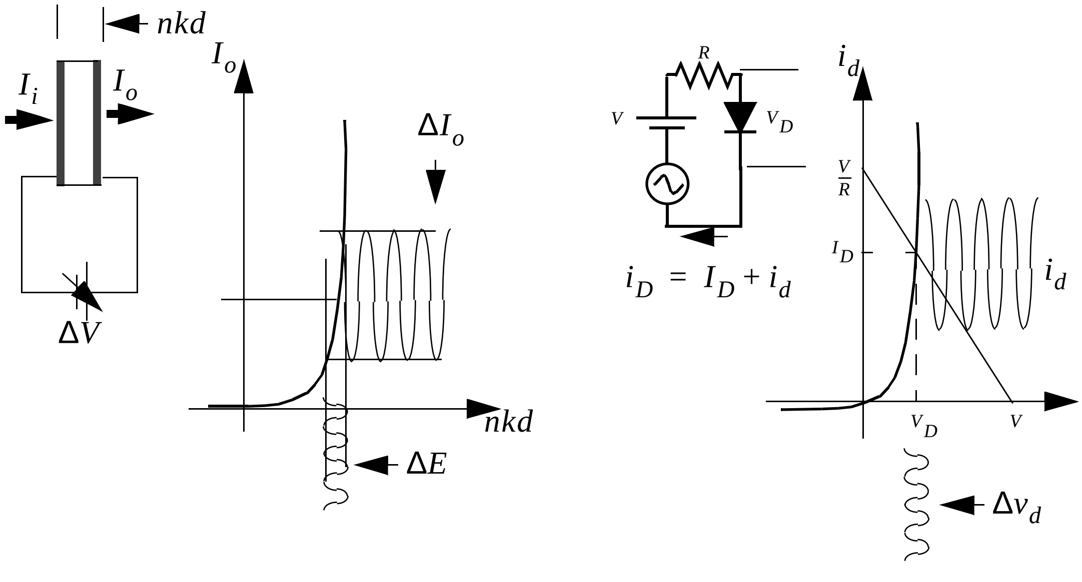
Matching impedance

Antenna matched to free space impedance

Maximizing the transmission by quarter wave film or so called anti-reflecting coating

Fig(4). Impedance matching in a microwave circuit, an antenna, and optical reflection from a flat surface are compared.

Concepts such as pulse modulation, time domain, frequency domain multiplexing and demultiplexing, and sampling theory are the same in optical and electrical communications and examples in both of these areas can be presented in typical communications lectures. In coherent optical communications, the concepts of heterodyne, homodyne, and superheterodyne can be presented in the same course where their electrical counterparts are being discussed. There are numerous examples in integrated optics[9] that are better taught in typical undergraduate electricity and magnetism courses.

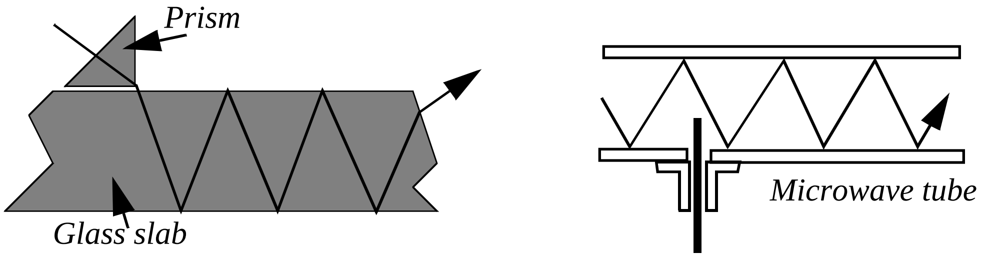


Fig(5). At the left, the optical transmission through a slab of ferroelectric and its transmitted intensity as a function of applied electric field is shown. At the right, the IV characteristic of a diode and its load line is shown.

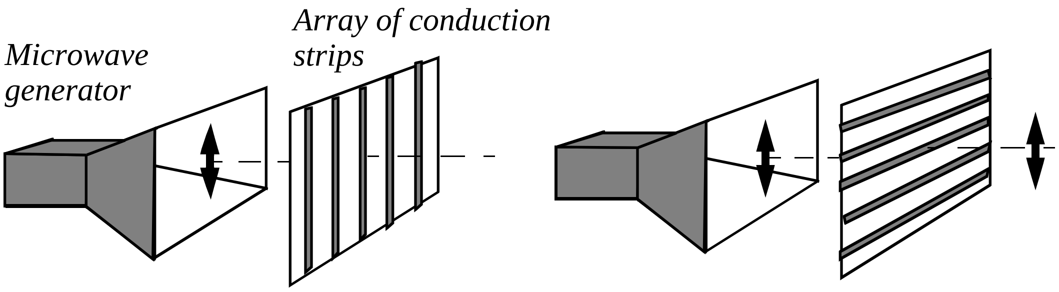
Laboratory and Class Room Demonstrations

Experiments in E&M courses, unlike the experiments in analog and digital electronic courses, are difficult and expensive. Probably the best way to get around these difficulties is optical demonstrations of E&M principles. Optical sources, such as light emitting diodes and semiconductor lasers, are much more readily available compared to radio transmitters and microwave generators. Optical propagation in an ordinary glass plate by prism coupling can be used to demonstrate the ideas of propagation in dielectric media, boundary conditions, and phase and group velocity. This is demonstrated in Fig(6) and compared with a microwave waveguide.

The topics of transmission through dispersive media, refraction, diffraction, and modal dispersion in E&M can be demonstrated more simply by using optical methods. Of course, there are situations where demonstrations using microwave devices can explain certain optical phenomena better than using optical methods. For example, optical polarization requires understanding of anisotropic medium which is not an appropriate topic for undergraduate studies in engineering. Such an idea can be easily demonstrated by using an array of conductive strips in front of a microwave source, as shown in Fig(7).



Fig(6). Using a prism to excite optical signals in a glass slab is compared with microwave excitation in a waveguide.



Fig(7). Demonstration of polarization using an array of conducting strips

In communication courses, the ideas of amplitude modulation, frequency modulation, wavelength division multiplexing, detection, and many other examples can be easily demonstrated by using optical methods. Such examples can be found in many textbooks in optical communications and signal processing

In more advanced electrical engineering courses, optical analog to digital convertors, optical memory, binary optics, and methods in optical computer and optical information processing can be demonstrated, simultaneously, with their electronic counterparts.

Conclusion

The expansion of optical methods in areas that traditionally have been only electrical is proceeding at a rapid rate. Optical approaches have found applications in all branches of electrical engineering. These include optical isolators which consist of optical transmitters and receivers and are major components in power and electronic systems; optical encoders and decoders that are used frequently in control applications; optical recording and information processing devices for electronic computation; and optical remote controls which are used in most electronic systems and are an integral part of home appliances. In some areas, such as communications, optical components are an overwhelming portion of the whole system and in other areas, electrical systems are being replaced by their optical equivalents. All this makes it impossible not to include optical concepts as an integral part of the undergraduate electrical engineering curriculum.

The examples presented in this paper are only a few of the many instances where optical and electrical systems complement each other and enhance the quality of undergraduate courses and curricula in the field of electrical engineering. Due to the essentially identical and comprehensively similar nature of optical and electrical systems, it is imperative that these two fields be presented in a coherent and simultaneous approach. This will allow the examples from one field to result in creativity and understanding in the other while avoiding the narrow focus of traditional electrical engineering.

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