Developing Photonic Integrated Circuits (PIC) Curriculum

by
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ABSTRACT

Photonic Integrated Circuits, or PICs, are circuits that utilize light instead of electrons for their functions. They are becoming increasingly important in modern systems. A number of students who graduate college would benefit from more exposure in their undergraduate years to PICs and other devices that use and provide context for the concepts they are learning.

For this project, this need was addressed by creating educational materials that may eventually be used in a curriculum for PH 1140 that incorporates PICs. The educational materials use simulations provided by the AIM Academy at MIT, and consist of a worksheet with conceptual questions about the wave concepts addressed by the simulations. In addition, a survey was created to assess the effectiveness of the current curriculum. The survey is intended for students that previously took PH 1140 to answer some questions about waves, many of which are based on common areas of confusion described in the literature. These students will serve as a control group to determine whether the current class can be improved.

ACKNOWLEDGEMENTS

I would like to thank Professor Douglas Petkie, whose guidance was invaluable in this endeavor. I would also like to thank the people involved with the AIM Photonics Academy at MIT for their simulations, which were a major part of this project.

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CHAPTER 1: BACKGROUND AND INTRODUCTION

Photonic Integrated Circuits

A Photonic Integrated Circuit, or PIC, is at its basic form a circuit that utilizes light instead of electrons for its functions; it performs optical operations on the light that flows through it. PICs use the visible-to-infrared portions of the electromagnetic spectrum. PICs are in use today; for example, they are used in telecommunications systems, which are beginning to use optical systems and fibers, for signal processing. [2] PICs are also a subject of active research, as scientists search for new ways to increase their efficiency and functionality. Since PICs are anticipated to continue being used in the future [1], it is deemed important that students become at least familiar with them during their college career. [2].

The most important component of a PIC is the optical waveguide. The optical waveguide serves to control the flow of the light which the circuit depends on. Cylindrical optical fibers are a common type of waveguide, consisting of a core (the material the light travels through) surrounded by cladding. The confinement of the light depends on the principle of total internal reflection: when the light hits the surface of the cladding, it must reflect as perfectly as possible in order to stay inside the waveguide and not escape through the cladding. Thus, the angle of incidence (the angle at which the light intersects with the cladding) must be greater than or equal to the critical angle of reflection (in order for the wave to propagate within the waveguide, the angle of incidence should be greater than the critical angle). The critical angle of reflection depends on the refraction indices of the core and the cladding. It is described by this equation:

$$\sin(\theta_c) = \frac{n_b}{n_a} \qquad \text{[eq 1]}$$

where θ_c = the critical angle, n_a = the refraction index of the core, and n_b = the refraction index of the cladding. [4] In order for θ_c to be a valid angle, the refraction index of the core must be greater than the refraction index of the cladding ($n_a > n_b$) by a significant amount (because if the ratio is too close to 1, θ_c approaches 90 degrees, which becomes impractical since the angle of incidence must be larger than this). [2]

Another measure of how well a waveguide contains light is the numerical aperture, defined by the equation

$$NA = (\mathrm{n}_\mathrm{a}^2 - n_b^2)^{\frac{1}{2}} \qquad \text{[eq 2]}$$

This also shows that the confinement depends on the difference between the refraction indices; the greater the refraction difference, the better the waveguide is at containing and guiding light. [2]

Current State of Photonics Education

It is valuable for undergraduate college students to learn, among other things, the context of their work and how the science and technology are used in real-world settings. A number of students are lacking in these areas when they graduate from college. [5] To combat this, curriculums throughout different colleges are beginning to include information about the cutting-edge concepts (like PICs) that students may work on in industry, so they are better prepared when they enter the workforce. There are a number of techniques for accomplishing this. The goal of this project was to continue this process with WPI's PH 1140 freshman curriculum for oscillations and waves.

One technique used is the utilization of computer simulations and software to enhance the students' learning. One such tool, the RAY simulation tool, is used in some higher-level college courses to help students understand and properly interpret ray diagrams. The RAY simulation can be used by the teacher in a set of exercises designed to facilitate understanding. Common difficulty areas experienced by students were taken into account when using RAY. [6]

Photonics Textbook

When developing the potential curriculum, the Photonics Textbook listed in reference [2] was incorporated. It contains useful information about refraction and the critical angle of reflection, some of which was described earlier in this report.

Description of Simulations

The AIM Photonics Academy has provided a number of useful simulations of wave concepts, including refraction, total internal reflection, and interference. Three simulations were selected for the purposes of this project, based on the expected skill level of the students. The three simulations were:

- Waveguide Fundamentals: Shows the effects adjusting the material of the cladding and core of a waveguide have on the confinement of the wave traveling through. When the difference between the refraction indices becomes too small, the wave escapes confinement. A similar effect occurs when the waveguide is made too narrow. The simulation also can show the effects of changing the waveguide width on the guide's ability to support multiple wave modes.
- Radial Bend: Shows the effects of increasing or reducing the radius of a curved waveguide on the confinement of the wave. A narrower radius harms confinement. The width of the waveguide itself can also be modified (leaving the radius fixed), and as before, making the waveguide too narrow will cause the confinement to fail.
- Y-Branch: An interference simulation. Note that for this project, only the Straight option in the Splitter section was used. The simulation portrays a wave moving in a waveguide, which is split into two different branches. The waves in the top and bottom branches gain or lose intensity, depending on the wavelength. The wavelength can be modified in the simulation, and the powers of both the original wave and the branches are shown. In the Combiner

section, the two branches are combined into one, where they interfere constructively, destructively, or somewhere in between, depending on the relative power of the two branches and the phase offset, which can be modified on the bottom branch. When there is no offset, the waves interfere completely constructively, and when the phase offset is 180 degrees (π radians), the waves are out of phase and interfere destructively.

A screenshot of the Y-Branch simulation is shown in Figure 1. Links to the simulations are provided in the Appendix. [7]

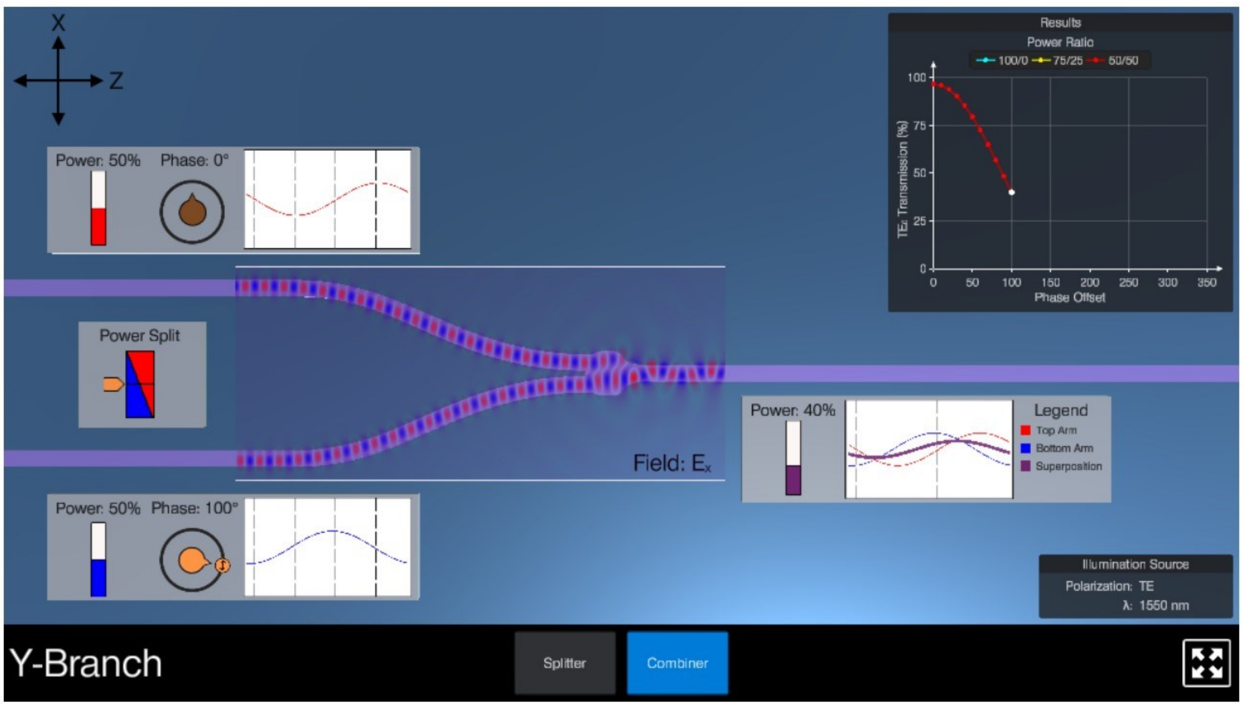

Figure 1 Y-Branch Simulation

CHAPTER 2: METHODOLOGY AND RESULTS

Formulation of Worksheets

The simulations have potential to help facilitate student understanding. It was decided that in the curriculum, the simulations would be paired with a worksheet of exercises that require simulation use to answer. It is hoped that students would find this useful in mastering the material.

Before creating the worksheets, common problems students have understanding waves were investigated. It was discovered that computer simulations have been proven to be useful in demonstrating the properties of waves, which was encouraging for the purposes of this project. Concepts that have caused difficulty (that the worksheets attempt to address) include trouble visualizing the wave, the relation of the amplitude of a wave and a confinement mechanism containing it (like a tube with a fixed radius), how a wave propagates through space over time, the phase of a wave, and the concept of superposition. The worksheet aims to mitigate these in various ways. [8]

All three of the simulations themselves show light waves propagating through space, which helps students visualize the behavior of waves. The amplitude of a wave does not depend on the confinement mechanism; it is possible, for example, for a wave's amplitude to be greater than the radius of a tube it is contained in. The purpose of containment is not to completely confine the wave within a mechanism (such as a waveguide), but to minimize power loss out of the waveguide as much as possible, and to keep the wave's trajectory mostly aligned with that of the waveguide. To address this, a question in the worksheet was added for Waveguide Fundamentals, asking about the amplitude of the wave compared to the height of the waveguide. It is clearly shown in the simulation that the amplitude of the wave is greater than the waveguide height, even when the wave is contained. Students can gain experience with the phase of a wave by manipulating the phases in the Y-Branch simulation, and there are several questions relating to phases (and superposition) in the worksheet, including a basic question of how a phase change affects a wave. The Y-Branch simulation also shows superposition in action, and there is a question asking whether the displacements or the amplitudes are added in superposition, directly addressing the possible problem area.

The simulations also are required to answer many of the questions: for example, for the Y-Branch simulation, one question directs the student to adjust the power split to 50/50 and cycle through the phase in the Combiner section, describing what happens. The worksheet is included in the Appendix.

Survey Formulation

To assess the usefulness of the current curriculum, a survey was created. This survey is intended for students who have already taken PH 1140. The intent is for these students to serve as a control group. The survey consists of 5 questions regarding refraction, reflection, and interference and superposition, a bonus question prompting students for applications of these concepts (an open-ended question, the purpose of which is to see how many students are familiar with PICs), an optional question at the end searching for feedback, and a question at the beginning prompting students for when they took PH 1140. For example, one conceptual question presents a diagram of two overlapping waves and asks students to identify points where constructive and destructive interference occurs. These questions were created with the problem areas described in [8] in mind as well, to measure students' grasp of the more difficult concepts. The questions are a combination of original questions and questions taken from other sources, like the *University Physics* textbook by Young and Freedman and the website PhysPort, which contains assessment questions. This survey is included in the Appendix of the final paper. [4, 9]

CHAPTER 3: FUTURE WORK

Curriculum

In the future, a curriculum for PH 1140 will be developed that incorporates PICs. The existing PIC curriculum uses textbook materials, online exercises, PowerPoint presentations, and exercises and labs to teach the material. The goal is to include the simulations and the worksheets at relevant points in the curriculum to provide context to the students as to how the wave concepts they're learning are useful. The online photonics textbook will also be used as it provides useful information on refraction and reflection as they apply to photonics. The PH 1140 curriculum would be augmented with the PIC simulations at around Week 3, where waves are introduced. In addition to the worksheet created during this IQP, questions from the *Physics for Scientists and Engineers* book by Randall Knight may also be utilized either in additional assignments or as augmentations to the existing assignments. [10]

Deployment of Survey and Worksheets

With approval from the WPI Internal Review Board, the survey will be deployed to students who have taken PH 1140, as detailed in the Methodology and Results section. In addition, in the PH 1140 class itself, the new curriculum will be used, and the students will also work through the worksheet and simulations, taking the survey before and after to see how the simulations affected their learning. The anticipated outcome is that the basic concepts tested in the survey will be reinforced by the simulations and worksheet exercises.

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7. AIM Photonics Academy, Massachusetts Institute of Technology.

8. Knight, Randall D., *Five Easy Lessons: Strategies for Successful Physics Teaching,* Pearson Education Inc., San Francisco, CA (2002).

9. Physport, www.physport.org

10. Knight, Randall D., *Physics for Scientists and Engineers: A Strategic Approach, Student Workbook,* Pearson Education Inc., United States of America (2004).

APPENDIX A

Simulation Links

https://s3.amazonaws.com/virtual-lab-silicon-waveguide/index.html (Waveguide Fundamentals)

https://s3.amazonaws.com/virtual-lab-radial-bend/index.html (Radial Bend)

https://s3.amazonaws.com/virtual-lab-y-branch/index.html (Y-Branch)

Worksheets

Sim 4 (Y-Branch) Activities

Splitter: Select Straight. Adjust the wavelengths and see how the transmission power of the E and B fields react, using the graph. What do the curves show about the E field versus the B field?

Combiner: Adjust the power balance of the top branch (red wave) versus the bottom branch (blue wave) using the power splitter. What happens to the relative powers of the branches?

Set the power splitter to 50/50 top/bottom. Use the phase dial on the blue wave to change its phase. Observe the window with the purple power meter; what does the purple wave in this window represent? What happens to the purple wave as the phase of the blue wave is changed (To see the effects, turn the phase dial in one complete cycle and see what happens throughout)? Can you explain why this happens? What is being added during superposition: displacement or amplitude, and why? What is the phase offset when the purple wave disappears? Try this for power balances of 75/25 top/bottom, and 100/0 top/bottom. What changes about the behavior of the purple wave?

In general, how does changing the phase affect a wave's propagation?

Sim 2 (Waveguide Bend) Activities

Radius: The diagrams and graph in the simulations show how well the wave is confined in the waveguide and the magnitude of the transmitted power. What happens when the radius size is increased and decreased (go to the two extremes to see the effect)? Why does this happen? Does the this apply to both electric and magnetic fields?

Width: What happens to the wave and transmission power when the width is decreased too much? Can you describe the curves representing the transmission power for the electric field and the magnetic field during a sweep of the width?

Sim 1 (Waveguide Fundamentals) Activities

Optical Confinement: See how changing the cladding and core materials affect confinement. In particular, see how close the cladding and core indices can get before the waveguide fails. The core is represented by the rectangle and the cladding is represented by the platform it's resting on. What is the equation for the critical angle of reflection? When is it defined? Knowing this, can you answer why the refraction index of the core must be significantly greater than that of the cladding? Also, what do you notice about the amplitude of the wave compared to the waveguide?

Single Mode: At different heights, observe the effect on the confinement factor when the width is changed. What effects do decreased widths and decreased heights have on the confinement potential of the waveguide?

Multi-Mode: With the height fixed, change the width and see what happens to the multiple modes. How is this shown on the graphs? Does this effect apply to both the electric and magnetic fields?

Worksheet Answer Key

Sim 4 Solution Key (Y-Branch)

Splitter: Select Straight. Adjust the wavelengths and see how the transmission responds using the graph. You should see that the E field's power doesn't change, but the M field decreases after around 1600 nm.

Combiner: Adjust the power balance of the top branch versus the bottom branch using the power splitter. Giving one branch more power will take power from the other branch; so giving the most amount of power to the top branch will take away almost all of the bottom branch's transmissions, and vice versa.

There is a dial where you can change the phase of the bottom branch's waves. While you do this, observe the window with the purple power meter; this shows the superposition of the top and bottom waves. Changing the phase on the dial causes the phase of the bottom wave (blue in the superposition window) to change relative to the top wave (red in the superposition window). This will cause the nature of their interference to change. At the beginning of the simulation, the red and blue waves are perfectly in phase (which is why the blue one isn't visible), adding completely constructively. When the phase of the blue wave is changed, their interference is no longer completely constructive and the power of the sum decreases. In the extreme case where blue is completely out of phase with red, the interference is completely destructive and the power goes to zero. The displacements at each point are added, not just the amplitudes. This can also be seen on the graph, which has a minimum of zero where the phase offset is in between 150 and 200 degrees.

The above description was for a 50/50 power split for top/bottom; also try this for 100/0 and 75/25 power split. For 75/25, since the top wave is stronger than the bottom wave, even when the interference is completely destructive the superposition still has power, which comes entirely from the top wave. For a 100/0 power split, since the bottom wave doesn't exist, its phase has no effect on the top wave and the superposition is constant.

Changing the phase of a wave offsets it by a cycle or fractions of a cycle.

Sim 2 Solution Key (Waveguide Bend)

Radius: Notice how when the radius is too small, almost all the energy is lost. This is because the angles are too small for critical reflection, so the light isn't reflected and escapes through the side of the waveguide. This simple concept is illustrated through the graphs and cross-sections, and applies to both the electric and magnetic fields.

Width: Observe how, for both E and M fields, making the width too narrow causes drastic loss in the field. While the E field flattens out in between 400-500 nm, the M field seems to peak at 800 nm and is on a decline after that. There is a tradeoff between maximum E power and maximum M power.

Sim 1 Solution Key (Waveguide Fundamentals)

Optical Confinement: See how changing the cladding and core materials affect confinement. Proper confinement that still allows the wave to propagate depends on the difference in refraction index between the cladding and the core, as well as the materials of the core and cladding, and is best when the cladding is SiO_2 and the core is Si. (While air provides more confinement, it isn't practical because the core needs cladding to rest on.) The indices of refraction need to be such that the angle of the light when it hits the interface between the cladding and core is always greater than the critical angle. The critical angle is defined by the equation $\arcsin(n2/n1)$, and is only defined when $n2 \le n1$, where, in the case of PICs, n2 would be the cladding's refraction index and n1 would be the core's refraction index. So, the index of refraction of the core must always be significantly greater than that of the cladding. Otherwise, internal reflection will not occur, and confinement becomes impossible. Of course, the amplitude of the wave is greater than that of the waveguide, since an electromagnetic wave can't be perfectly contained by a waveguide.

Single Mode: At different heights, observe the effect on the confinement factor when the width is changed. Smaller heights and smaller widths mean smaller confinement potential of the waveguide.

Multi-Mode: With the height fixed, change the width and see how the waveguide loses the ability to support multiple modes when the width is too small. Two curves appear on the graph; one of them represents the second mode, and it vanishes when the width decreases enough. This happens with both the electric field and the magnetic field.

Survey

This survey is for previous students of 1140. It's meant to gauge how well they remember certain concepts.

Learning outcomes:
Describe how the critical angle depends on n_a and n_b (for question 1)
Be able to say when total internal reflection happens based on the refraction indices (for question 2)
Understand how the difference in refractive indices affects internal reflection (for question 4)
Be able to apply the principle of superposition to two waves (for questions 5 and 6)

1. When did you take PH 1140? (Drop-down list containing options: Fall 2019 B-term; Spring 2019 D-term; Fall 2018 B-term)

2. When light originates in material a, with index of refraction n_a, what are the requirements for critical reflection?
    a. $n_a > n_b$ and $\theta > \theta_c$ (where θ_c is the critical angle, θ is the angle of incidence, and b represents the next material the light passes into)
    b. $n_a > n_{b,}$ and $\theta < \theta_c$
    c. $n_a < n_{b,}$ and $\theta > \theta_c$
    d. $n_a < n_{b,}$ and $\theta < \theta_c$

3. Is there total internal reflection in the following situation? Why?
Light propagating in water (n = 1.33) strikes a water-air interface at an incident angle of 70 degrees. n of air = 1. (from University Physics by Young and Freedman)

4. **BONUS:** Can you name an application of these concepts? (Open-ended question)

5. In a waveguide containing a light wave, the refraction index of the material the wave is moving through must be significantly greater than the refraction index of the cladding material surrounding it. Why is this?
    a. Significant refractive index difference leads to decreased confinement
    b. Significant refractive index difference leads to increased confinement
    c. Insignificant refractive index difference leads to decreased confinement
    d. Insignificant refractive index difference leads to increased confinement

The following questions refer to Figure 1 (shown below)

6. Wave 1 (in red) and Wave 2 (in blue) are moving through the same medium and undergoing interference. Select all the points where constructive interference applies.
    a.
    b.
    c.
    d.
    e.
7. Wave 1 (in red) and Wave 2 (in blue) are moving through the same medium and undergoing interference. Select all the points where destructive interference applies.
    a.
    b.
    c.
    d.
    e.

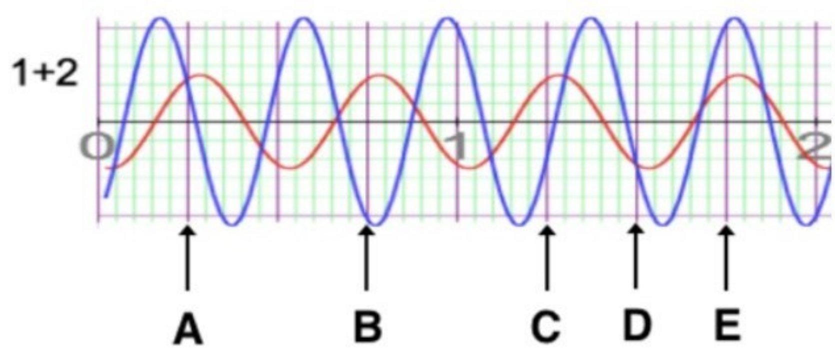

Figure 1

OPTIONAL: We would appreciate any feedback you can give on this survey (open-ended question):

Estimated time for completion: ~10 minutes