CAD-Supported University Course on Photonics and Fiber-Optic Communications

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ABSTRACT

The highly competitive global photonics industry has created a significant demand for professional Photonic Design Automation (PDA) tools and personnel trained to use them effectively. In such a dynamic field, CAD-supported courses built around widely used industrial PDA tools provide many advantages, especially when offered through tertiary education institutions (which are ideally suited to producing the future workforce of the Photonics industry). An objective of VPIsystems' University program is to develop tertiary level courses based on VPIsystems' WDM transmission and component modeling software tools. Advantages offered by such courses include: visualizing and aiding the understanding of complex physical problems encountered in the design of fiber-optic communication systems; virtual laboratory exercises that can accurately reproduce the behavior of real systems and components without the prohibitive infrastructure and maintenance costs of real laboratories; flexibility in studying interrelated physical effects individually or in combination to facilitate learning; provide expertise and practical insights in areas, including industry-focused topics, that are not generally covered in traditional tertiary courses; provide exposure to, currently, the most widely used PDA tools in the industry. In this paper, details of VPIsystems' University program and its CAD-supported Photonics courses will be presented.

Keywords: University course, tertiary education, training, photonics, fiber-optic, CAD, optical communications, photonic design automation

1. INTRODUCTION

The explosive growth in the demand for telecommunications capacity in the last decade has driven the progress of fiber-optic communications and photonic systems. The relatively simple single wavelength channel point-to-point fiber-optic links of the 1980s, once regarded as a media of virtually inexhaustible capacity, are inadequate for meeting the data intensive capacity demands of the Internet of the 1990s. Wavelength Division Multiplexing (WDM)[1] has provided the means to satisfy that demand, by scaling the capacity upwards through the transmission of multiple different wavelength channels within a single fiber-optic link. Continued and exponential growth in the demand for capacity is pushing the performances of WDM systems and their components to the limit. These systems now have to be designed to operate over extended wavelength ranges (to transmit more channels), at higher optical powers (to increase the unrepeatered transmission distance) and at higher transmission rates. As a result, the analysis, design, design verification and testing of these systems are very challenging. This is because in addition to attenuation and group velocity dispersion, a host of fiber and device higher order as well as nonlinear effects, which become significant at higher optical powers, wider bandwidth and higher bit-rates, must be taken into account. The complicated calculations involved in accounting for these higher order and nonlinear effects necessitate the use of computer simulations.

The simulation of a fiber-optic communications system involve the detailed modeling of its various components, from the transmitter, fibers, multiplexers, cross connects, amplifiers to the receiver. The design of just one of these components can significantly and directly affect the performance of the system. It would be too costly and time consuming to develop and optimize every component by testing it within a whole system, via a series of prototypes. There is also the cost of comparative testing between competing component technologies, which may be impossible as some of these technologies still have not yet made the transition from the laboratory to mass production.

The highly competitive nature of the global photonics industry, however, demands rapid development and improvement of component as well as system performance at reduced costs. New design methods[2, 3] must be found to achieve these goals. The tight specification of the performance of all components can ensure the required performance of the overall system, but these would lead to an overly conservative design that would not be sustainable in a highly competitive industry. A feasible alternative is to use computer-aided-design (CAD), to substitute for the traditional hardware prototyping with software simulations[3, 4], to develop and optimize photonic components and systems.

The significant cost savings that can be achieved have resulted in a push in the development of CAD software for photonics design automation (PDA). PDA software tools such as those developed by VPIsystems are based on very well researched and published mathematical models. Much testing of these PDA tools and the verification of their simulation results had been performed, against published experimental results and measures, to ensure their veracity and accuracy. Built into these PDA tools are also the expert knowledge, analytical methods and design rules that are based on previous successful designs as well as the experience of system and component specialists. This same body of knowledge, know-how, experience and CAD software tools, which helps engineers and scientists in various industrial organizations and research establishments do their jobs in analyzing and design photonics systems and components, can be applied with equal facility to teach students in University/tertiary courses. In this paper, we will focus on the application of VPIsystems PDA tool in a CAD assisted university course in photonics and fiber-optic communications.

2. THE VPISYSTEMS PHOTONIC DESIGN AUTOMATION TOOLS

In this section, details about the VPIsystems PDA tools for the physical layer are provided to show the range of topics in which these tools can be used for teaching. They are *VPItransmissionMaker™ WDM*, *VPItransmissionMaker™ Cable Access*, *VPIcomponentMaker™ Fiber Amplifier* and *VPIcomponentMaker™ Active Photonics*.

VPItransmissionMaker™ WDM is used to simulate of all types of optical communication systems (WDM, TDM, soliton) at the physical level. Over 500 component and subsystem modules are supplied that can be assembled to form transmission links and optical networks. These modules include optical fibers, laser sources, passive network devices (couplers, splitters, circulators, multiplexers etc), optical amplifiers, receivers, signal-processing elements, and data visualizes (optical spectrum analyzers, oscilloscopes, bit-error-ratio (BER) estimators, eye diagrams etc). These modules are based on very well researched mathematical models and are solved with sophisticated numerical techniques to provide accurate and fast simulation results. Additionally, practical, experimentally measured data and component responses may be incorporated into the simulations in order to produce realistic results.

VPItransmissionMaker™ Cable Access provides a specialized set of tools for the analysis and design of cable access and cable TV networks, as well as the simulation of analog, digital, mixed-analog-digital, HFC, DOCSIS and novel access technologies focused on subcarrier multiplexing. The effects of modulators, lasers, feedback, fiber dispersion and nonlinearities can be included.

VPIcomponentMaker™ Fiber Amplifier covers the specialist topic of doped-fiber, Raman and hybrid amplifier designs, which can be constructed from many components and multiple stages. It also provides black box model abstraction and uses the latest sophisticated algorithms for obtaining simulation results for long amplifiers quickly and accurately.

VPIcomponentMaker™ Active Photonics simulates large-signal dynamics of multi-element photonic circuits and lasers over a wide spectral bandwidth and includes time dependence, bi-directional interactions, dynamic effects, and transient effects. It is used for the detailed analysis and design of transmitters, optical signal processors, wavelength converters, ultra-high speed photonics circuits and semiconductor optical amplifier applications.

As described above, the PDA tools cover a wide range of topics relevant to the teaching of Photonics. Also supplied with these tools are a wide range of application demos that may prove invaluable as teaching aids. These demos are selected for their:

- Use as templates for standard problems in well-known industry areas such as metro, long-haul and submarine WDM systems
- Ability to investigate advanced problems such as polarization mode dispersion (PMD), optical crosstalk, spectrally-efficient modulation techniques and bi-directional Raman amplifiers
- Insight into simulation techniques and the selection of the most appropriate modules for a simulation task
- Tutorial value, both in component operation and simulation technology.

The four PDA tools described previously are used to capture a design and the relationships between components and systems, and this is done in the form of schematic diagrams (Figure 1). This provides a graphical user interface where various components of a transmission link or photonic system may be laid out and connected.

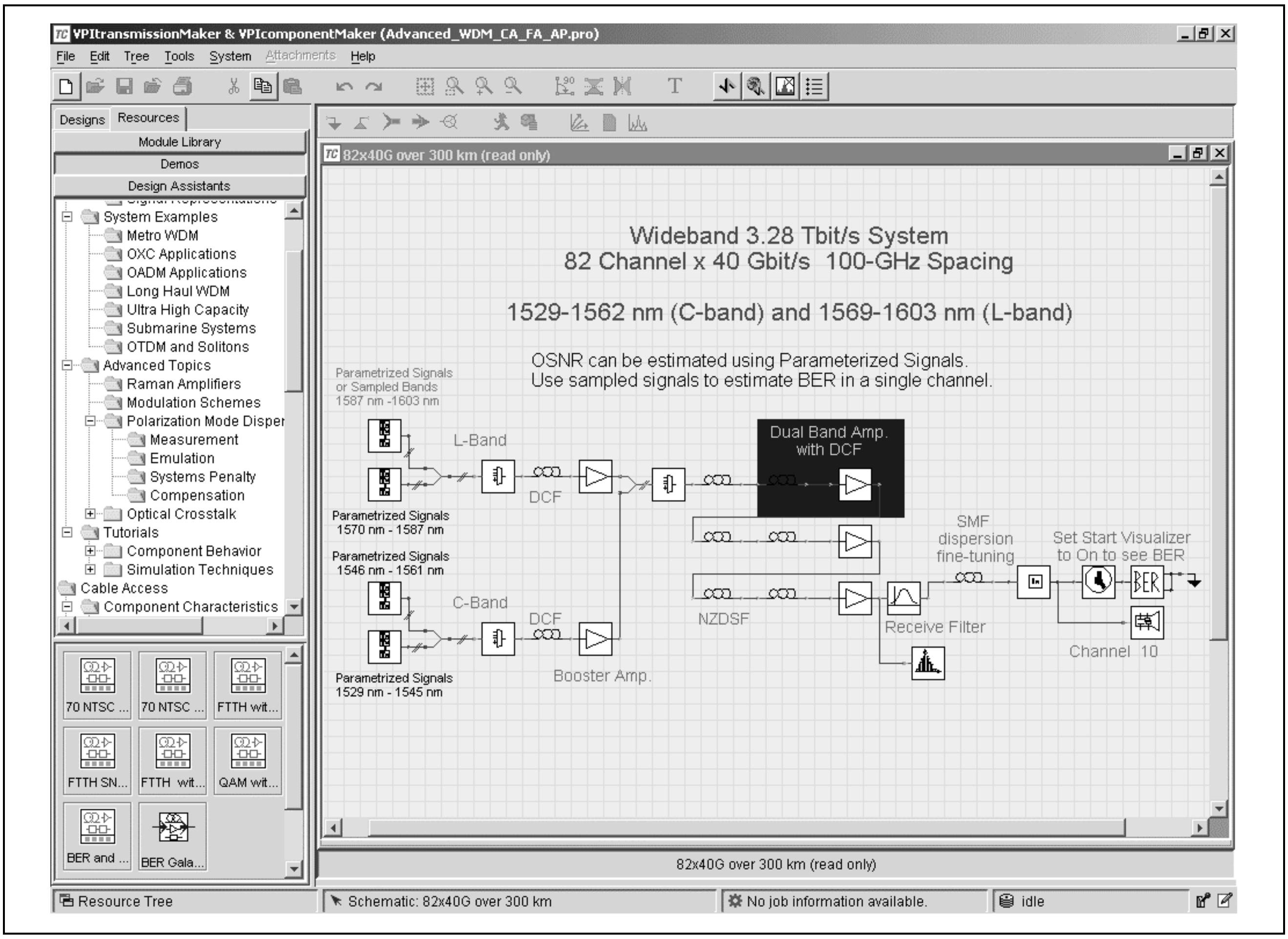

Figure 1: The VPIsystems PDA tool Graphical User Interface

Other useful features that have been incorporated into the VPIsystems PDA tools include:

- Programmable design assistants and wizards, which help with task automation. This include laying out modules, setting up standard parameter values, laying out systems with standard topologies, carrying out standard metrics and system verification tests, performing global component substitution and so on.
- Parameter sweeps for assessing system sensitivity to one or more parameters, e.g. BER vs. optical amplifier span length, or power penalty due to drift in component specifications etc.
- Module sweeps for component comparison within a system, e.g. the effect of different amplifier designs on the system BER performance etc.
- A scripting language to enable more sophisticated parameter sweeps and design optimization.
- The integration of third party software for greater flexibility, and the incorporation of existing, and/or proprietary, numerical component/system modules (Matlab, C++ and Python).

The schematics, designs, and data generated by the PDA tools, and any associated documents (such as *Microsoft*^{TM} Word, Excel, Power Point and other third party software etc) need to be managed, and this can be done with the *VPIdesignManager*^{TM}. It is part of the *VPIdesignCenter*^{TM}, which integrates all four of the aforementioned PDA tools to provide a single, integrated platform that acts as an engineer's working environment. Additionally, *VPIdesignCenter*^{TM} enable teams of people to work collaboratively within a common framework and access all required documents and tools (PDA and other third party software) easily, in the correct context and place. Features for project management, to manage data flow, to track changes and for document versioning are also provided to make it easy to coordinate the activities and efforts of many and a diverse range of personnel that is typical in a large company. These features may be easily adapted for the management of student projects, assignment submission, dissemination of information and so on.

3. APPLICATION OF VPISYSTEMS PDA TOOLS IN TEACHING

In the previous section, the details and features of VPIsystems PDA tools and the *VPIdesignCenter*^{TM} were briefly introduced, in the context of their usage in the industry and in research establishments. Here, the application of those tools in a CAD-supported university course on photonics and fiber-optic communications will be explored.

The first benefit of the application of PDA tools in the teaching of a photonics course is visualization and the understanding of complex physical problems encountered in the design of fiber-optic communication systems. A set of visualization modules supplied with VPIsystems PDA tools enable various types of data to be displayed in a variety of formats (Figure 2). For example, the waveforms of the optical pulses that make up an optical data stream can be shown as an oscilloscope trace or an eye diagram, and its spectrum displayed using an optical spectrum analyzer. The effects of polarization may be plotted on a Poincaré sphere. Simulated measurements may be plotted using an X-Y plotter, and histograms may be used to analyze the distribution of 1s and 0s in a digital signal. In short, the various data visualization formats that one can expect to see from practical laboratory equipment can be reproduced with PDA tools.

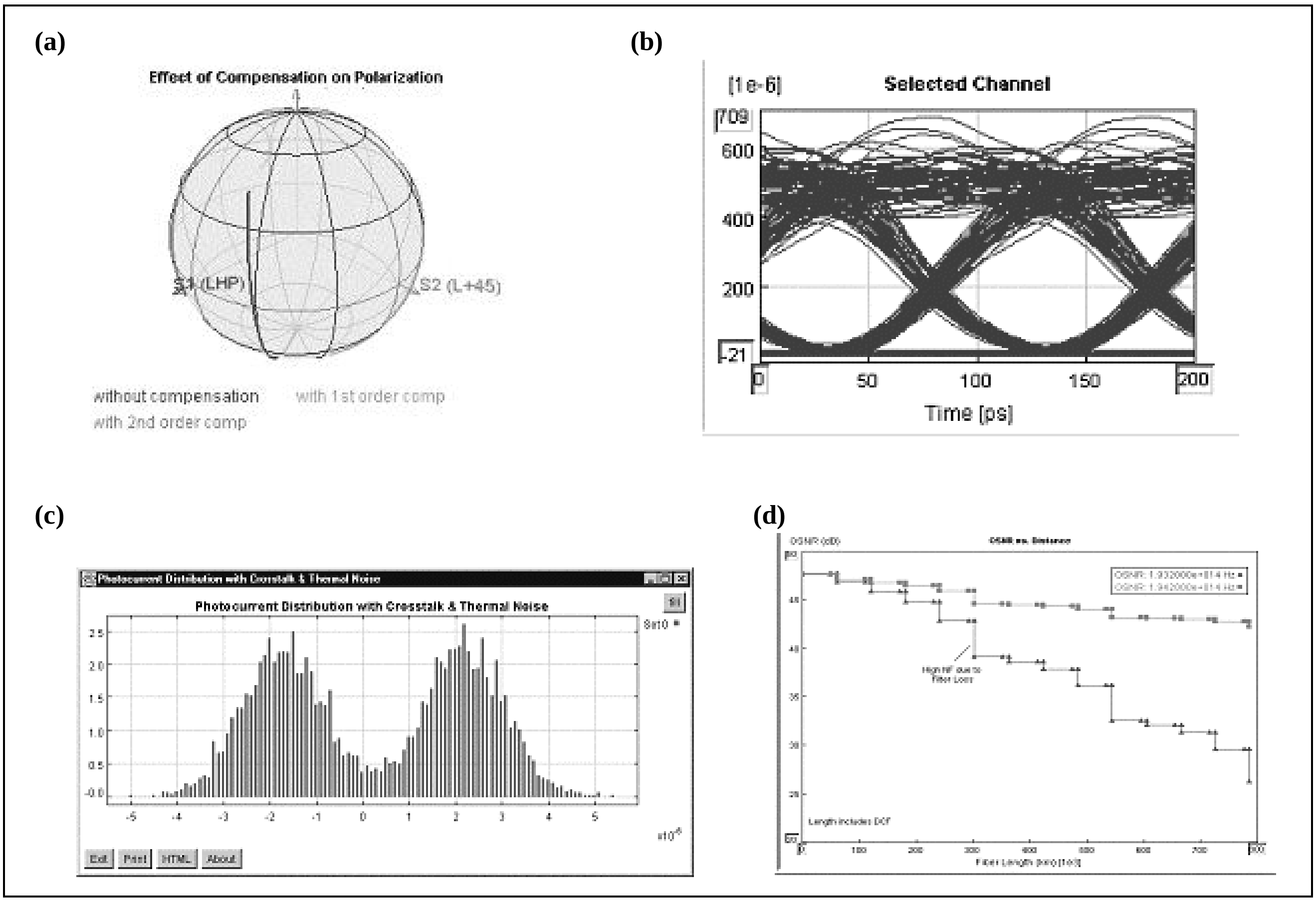

Figure 2: Examples of data visualization with VPIsystems PDA tools – (a) Poincaré Sphere visualization of the Stokes Parameters, (b) Eye Diagram of a pulse stream, (c) Histogram visualization of bit distributions, (d) X-Y plot of OSNR vs. Fiber Length

Most educators understand the value of live practical demonstrations in the classroom, and this leads to another advantage of the use of PDA tools for teaching. With computer simulations, live "virtual laboratory demonstrations" may be carried out easily, literally at the touch of a button, without the obstacles that accompany the transportation of expensive real equipment from the laboratory to the classroom. Additionally, live demonstrations of experiments, equipment or systems that are impossible to move to the lecture theatre can be performed via simulations. The data and system behavior visualization capabilities of PDA tools, plus the judicious use of additional teaching aids such as animation, video, charts, etc., can truly provide a greatly enhanced learning experience for students.

Secondly, the sophisticated PDA tools of today, which are capable of accurately reproducing the behavior of real systems and components, can provide a feasible substitute to real laboratory experience, without the prohibitive infrastructure and maintenance costs. Photonic components, systems, test and measurement equipment, consumables and the infrastructure to house them are prohibitively expensive. For example, a 10 Gbit/s BER test set can cost several hundred-thousand dollars, sampling scopes with high speed sampling heads and WDM optical spectrum analyzers each cost the order of a hundred-thousand dollars etc. Even the most generously funded universities of the world would be hard-pressed to set up well-equipped photonics laboratories with reasonably up-to-date equipment for their research staff and postgraduate students. Such astronomical equipment and maintenance cost, plus the fragility of expensive components such as laser chips, receivers, delicate gratings, lenses as well as the test and measurement equipment etc., makes it virtually impossible, at present and in the near future, to provide practical laboratory-based photonic teaching to growing numbers of undergraduate students.

With thoughtful preparation and an innovative approach, not only do PDA tools provide a means of reproducing a reasonable, albeit virtual, laboratory-learning environment for students, but they will also provide flexibility for the universities and save time as well as reduce maintenance cost. For instance, simply loading a new schematic into a computer can change the configuration of virtual laboratory experiments. The time consuming tasks of setting up, resetting and maintaining lab equipment or experimental rigs for a large number of laboratory experiments can be reduced. The nightmare of scheduling laboratories around a limited number of equipment and laboratory space can thus be avoided with PDA tool powered virtual laboratories. Carefully designed virtual lab experiments can be used to train students for the real thing, and this can greatly reduce accidents and the cost of equipment damage or wear-and-tear. Students can play around with the settings of virtual equipment, thus allowing them to explore without the fear of equipment damage. This mode of learning can foster in students the ability to think innovatively and creatively.

The cost of upgrading aging laboratory experiments and equipment, or even simply the cost of periodically maintaining and calibrating equipment, are reduced via the use of PDA tools. Any cost reduction will benefit universities and students alike, in that the money saved can be invested in new equipment and providing access to a greater number of students to photonics learning experience that can be nearly as good as the experience gained in a real laboratory.

Thirdly, another feature of computer simulations is the capability of switching on and off various physical effects to provide invaluable insights and assist students in gaining a deeper understanding of the behavior of photonic devices and systems. From a teaching perspective, this is traditionally achieved by solving simplified equations (that govern device or systems behavior) with the appropriate physical parameters set to zero or omitted. Students can then be guided through the simplified analytical solutions. This approach is good for showing basic effects (for example, fiber attenuation or dispersion), but the mathematics become rapidly intractable with the increasing device or system complexity. Furthermore, this separation and isolation of physical effects in a real experiment is generally difficult, if not impossible. Numerically modeled physical effects, such as fiber dispersion, nonlinearities, amplifier noise and so on, can easily turned off by setting certain physical parameters to zero. Also, PDA tools can simulate far more complex system and device behavior, compared with analytical solutions of simplified device/system equations. Alternatively, setting the appropriate parameters to values that are higher than normal can emphasize certain physical effects, and this is hard to do in a real experiment or demonstration.

Apart of the pedagogical advantages, the use of PDA tools also exposes students to expertise and practical insights in areas, including industry-focused topics, that are not generally covered in traditional tertiary courses. For example, VPIsystems PDA tools are currently the most widely used in the photonics industry. Much of the development of those tools, and the expert knowledge built into them, are driven by the needs of the industry. Students gain the advantage of being trained in tools that are already in use in the industry and in becoming familiar with design rules and other methods that are used by industry personnel. With *VPIdesignCenter™*, students can be exposed to common industry work practices such as working in teams and in shared workspace, managing projects, document management and version control. Lecturers, tutors, laboratory demonstrators and so on will also benefit from using *VPIdesignCenter™* to manage their classes, laboratories and student project groups.

4. THE VPISYSTEMS UNIVERSITY CURRICULUM

The VPIsystems University Program is targeted at major universities and other non-profit research centers around the world to facilitate the deployment of the next generation of optical components, systems and networks. The primary focus of the program is to build up and leverage long term partnerships in the areas that include academic curricula development, PDA tool capability and application enhancement, and training. At present, academic institutions use VPIsystems' PDA tools for classroom demonstrations, simulation of laboratory experiments, numerical simulation-based research and design optimization. In line with the program, we collaborate with interested universities in the integration of our PDA tools into their electrical engineering and photonics academic programs and curricula.

The VPIsystems University Curriculum is an initiative of our University Program, with the long-term goal of realizing a pool of high quality education/teaching/course material based on VPIsystems PDA tools. The material will cover a multitude of topics and applications in Photonics and Optical Communications, which will be available for use by the academic participants of our University Program who specifically sign up for the University Curriculum. It is envisaged that this course material will also be available to be adapted, modified, expanded and upgraded by participating Universities to suit their own unique educational and teaching needs. An important short- to mid-term goal is to actively engage with members of the University Curriculum in the development and expansion of the pool of course material.

In order to initiate the development of viable tertiary level course material based on VPIsystems PDA tools, we have contacted many members of our University Program, circulated questionnaires and gathered a significant amount of information pertaining to their education and teaching needs, as well as their interest in becoming part of the University Curriculum. From this information and past reports from them on their application of our PDA tools, we have begun the development of a generic Optical Communications/Photonics course, to serve as a starting point. It is our vision that this seed pool of course material will act as a model for future development, to be undertaken by participating Partner Universities and also in collaboration with VPIsystems.

5. PRESENT ACHIEVEMENTS AND FUTURE WORK

VPIsystems developed the first version of the university course in photonics and optical communications to be available for evaluation and use in teaching trials by members of the University Curriculum. The course is designed to teach the basics of Photonics using VPIsystems PDA tools as discussed previously in sections 2 and 3, and the advantages of such a course have also been described therein.

The course material is broken up into modules, each containing a set of lecture slides and a set of guided exercise notes. Both the slides and exercise notes are produced using *Microsoft®* PowerPoint format. Key slides in the lecture notes of each module, particularly those describing theory or physical phenomena that are hard to understand, are animated. The animation is designed to aid the lecturer in presenting those difficult concepts. Additionally, each lecture slide (except for the title slides, see Figure 3) have lecture notes attached to them that provide more information which can be used by the lecturer to tailor his or her delivery of the lectures. The lecture slides are ready for immediate use, without any modifications, to deliver a lecture on a particular topic. Alternatively, they can be modified and adapted to suit particular course requirements. Thus, members of the VPIsystems University Curriculum who decide to base their course on this generic photonics course can save considerable amount of effort in preparing their lecture material.

The exercise notes (Figure 4) of each module of the photonics course guide students through a set of virtual lab exercises that use the VPIsystems PDA tools to explore the key ideas and concepts presented in the lecture slides. Files are supplied with these notes containing various simulation schematics that are referred to and used in the exercises. These setups are saved using the portable VPIsystems vmi-format. They and can be imported for immediate use into any licensed installation of the VPIsystems PDA tools that they have been designed for.

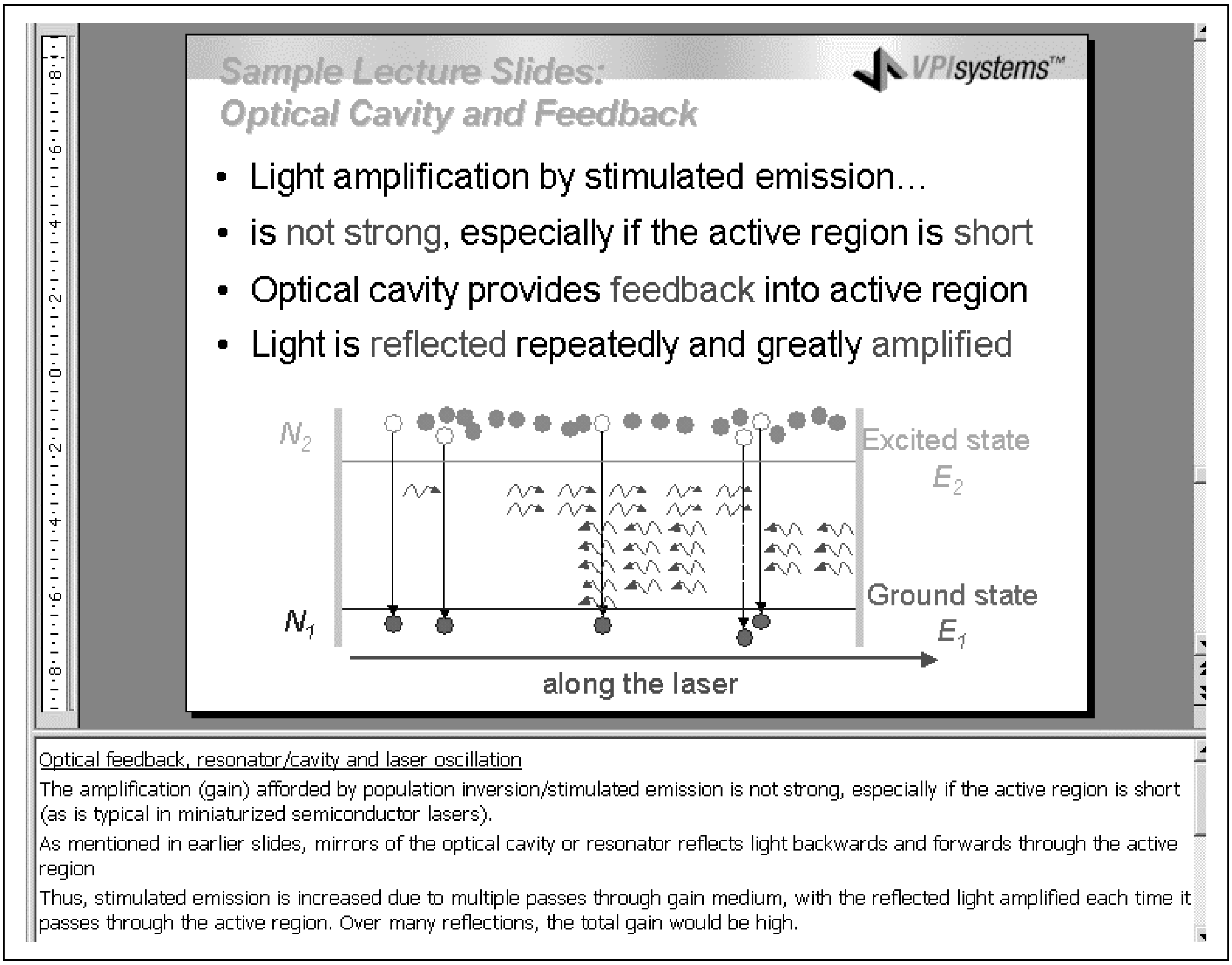

Figure 3: A sample lecture slide from one of the modules in the VPIsystems Photonics/Optical Communications Course

From the information in questionnaires that were returned to us from members of our University Program, we have found that the length of each classroom session varied from one to two hours. As such, each module of the VPIsystems course is designed to be about 90 minutes long: 30 to 45 minutes on the lecture depending on the topic, 45 minutes on the guided exercises, and depending on the time left, up to 15 minutes of self-test questions. The exact length of the presentation of the lecture part of each module plus the time required for the guided exercises will depend on the requirements of the individual lecturers and Universities. Most modules will have enough material for longer presentations if necessary, and this is also not including modifications and additional material that individual lecturers might incorporate into their presentations.

Course modules are designed so that they can be easily adapted and flexibly put together to create courses that suit various requirements, such as 1-semester, 2-semesters or summer-semester courses, at introductory, or advanced levels and so on, of various universities and other tertiary institutions. All of the completed questionnaires that we received indicate that the preferred length of a photonics course is one semester. On a weekly basis, courses are broken down into between two to three lectures (2 to 4.5 hours), one to two tutorials (1 to 2 hours) and/or one laboratory session (2 to 3 hours). These figures aggregate to weekly contact hours of a minimum of 5 hours to a maximum of 9.5 hours, though all the courses that we have polled so far varied between 6 to 8 contact hours per week.

In the initial round of development, we have prepared 10 modules, and their titles are:

- Introduction to Fiber-optic transmission I
- Introduction to Optical Fibers
- Introduction to Receivers
- Systems I – Introduction to WDM Systems
- Measurements II – Bit Error Ratio (BER) Estimation
- Introduction to Fiber-optic transmission II
- Introduction to Transmitters
- Introduction to Optical Amplifiers
- Measurements I – Basic Photonic Measurements
- Systems II – Introduction to Cable Access Systems

Detailed descriptions of these 10 modules are beyond the scope of this paper, but are available from us as a separate document. These 10 modules are aimed at students in the penultimate or final year of their undergraduate course in Engineering or Science. At the time of writing this paper, preparations for the distribution of these 10 modules of the VPIsystems photonics course to members of the University Curriculum are being made.

It the vision of VPIsystems that this initial pool of course material will act as a catalyst for future development of course material, to be actively undertaken by various interested universities and in collaboration with VPIsystems. The development of future modules could also incorporate teaching and educational materials that will be suitable for not just undergraduate courses, but also postgraduate courses.

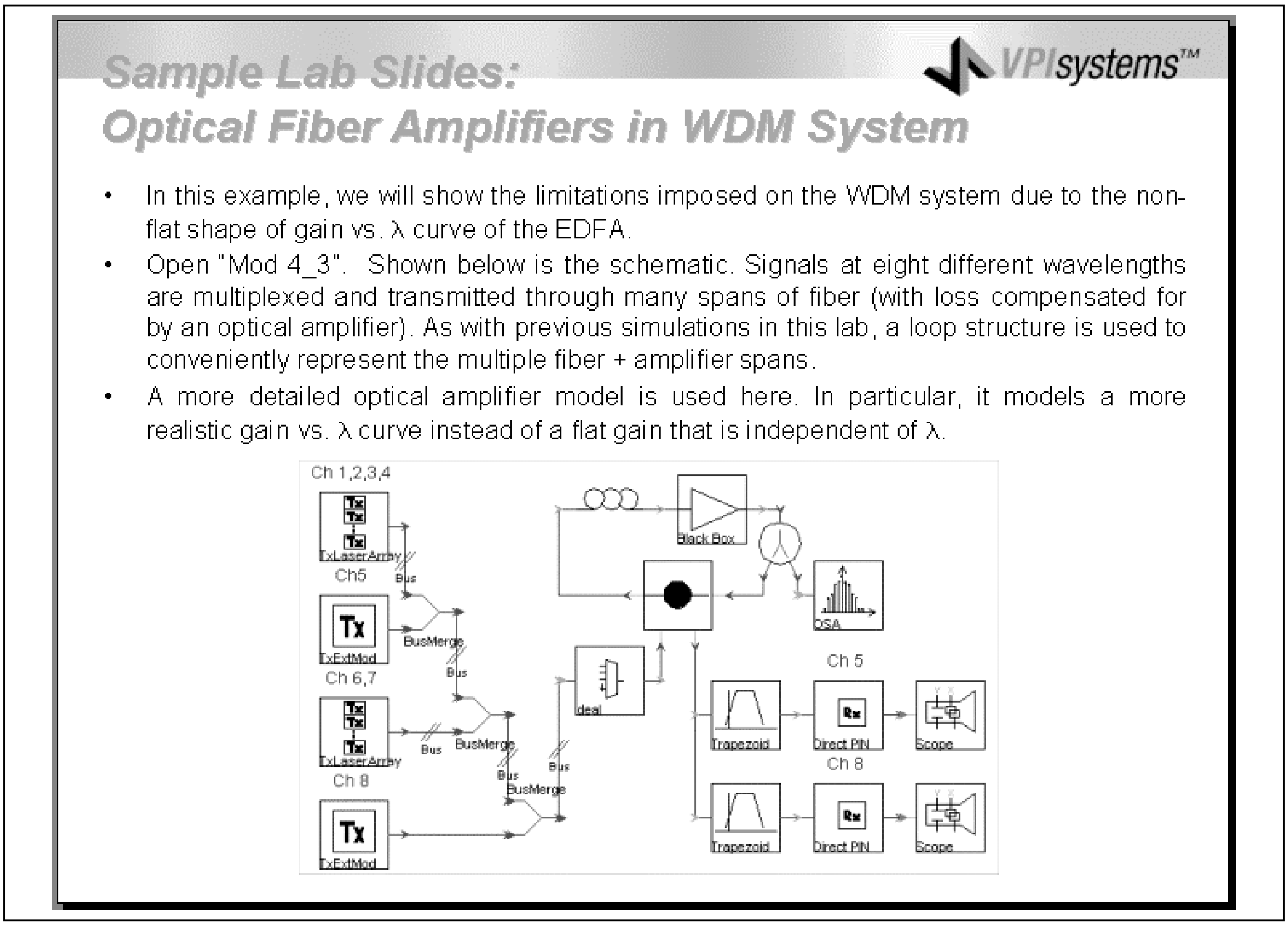

Figure 4: A sample guided exercise slide from one of the modules in the VPIsystems Photonics/Optical Communications Course

6. CONCLUSION

The exponentially increasing demand for telecommunications capacity in the last decade has driven the progress of fiber-optic communications and photonic systems. A highly competitive global photonics industry has grown to supply, support and satisfy this demand. In turn, this has created a significant demand for professional Photonic Design Automation (PDA) tools, along with the personnel trained to use them effectively, to reduce the development cycle as well as the cost for new devices, systems and networks that will be capable of meeting the capacity demand.

The same PDA tools can be used to educate and train potential future members of the photonic industry workforce. CAD-supported University courses that employ widely used industrial PDA tools provide advantages to students that include: visualization aids for the understanding of complex physical problems encountered in the design of fiber-optic communication systems; a means to study and understand complicated interrelated physical effects individually by turning off all other effects; exposure to expert knowledge, practical insights and industry-focused topics built into PDA tools; and access to a virtual laboratory experience that allow creative learning and exploration of simulated device or system behavior that will be a good form of preparation for the real experimental work.

For those involved in University education, the use of PDA tools also brings many advantages, which include the capability of: offering high quality photonic teaching to a wider group students, particular those at the undergraduate level; easily carrying out live, albeit virtual, experimental or laboratory demonstrations in the classroom without the difficulties associated with the setting up, transportation and the running of real experiments; providing rapid feedback to reinforce learning via visualization and animation of theory or concepts that are difficult for students to understand; reduce the infrastructure, maintenance, calibration, upgrading and replacement costs of laboratories; offering a virtual laboratory-based courses without the astronomical costs associated with expensive photonic equipment; and easy management of classes, laboratories, student project groups and so on.

Finally, the University Program and the University Curriculum initiatives of VPIsystems have been introduced in detail in this paper. The application of VPIsystems PDA tools in aiding the Photonics teaching has been discussed, including how various features, models, built-in demonstrations and expert knowledge can be adapted and applied for educational purposes. The generic VPIsystems photonics course has been described and it is intended as the initial source of material, based on VPIsystems PDA tools, to initiate long-term collaborations with Universities in developing a large and comprehensive range of University photonic education material.

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