Executive Summary

Program Plan Progress Summary
1.2. Task I: All Optical Tunable Wavelength Converter
1.2.1. Digital Chirp Measurements
1.2.2. Regenerative Properties and Dynamic Range of the Wavelength Converter
1.2.3. Digital and Analog Wavelength Routing Demonstrations
1.2.4. Protection Switching
1.2.5. 2-stage Wavelength Conversion Experiment Using the Monolithically Integrated Tunable Wavelength Converter

Task II: Filter/Mux/Router
1.3.1. TIR and Disc Micro-resonator Filters Compatible with InP Planar Integration Platform
1.3.2. Low Loss TIR Mirrors and Waveguides for InP Planar Integration Platform

Task III: OEOIC-WC
1.4.1. Directly Modulated SGDBR Wavelength Converters
1.4.2. Monolithically Integrated External Modulator Wavelength Converters

Table of Contents

Page 1
1.5. Wafer Processing Subcontract (Agility Communications) ........................................ 30
2. Publications ................................................................................................................. 30
3. Programmatic Interactions and Collaborations ............................................................. 31
  3.1. Test Facility: MIT Lincoln Labs ............................................................................... 31
  3.2. Architecture Study: MIT ....................................................................................... 31
4. Patents ......................................................................................................................... 31
5. Appendix A: Program Management Plan for Baseline Period ...................................... 32
6. Appendix B: Budget Summary for FY02-FY03 .............................................................. 33
Executive Summary

The scope of this program is to develop and demonstrate chip-scale integrated wavelength conversion and routing functions on a common substrate. The wavelength converters and routers developed will be photonic integrated circuits on InP substrates. The wavelength converters and routers will be compatible with both analog and digital transmission requirements. Issues involved in integration will be studied. Three classes of device will be investigated. The program is organized and managed by sub-area according to these three classes of device:

- **Sub-area I** (AOWC): In-plane SOA interferometric wavelength converter.
- **Sub-area II** (Filter/Mux/Router): Wavelength router and multiplexers based on filter and interferometric technologies.
- **Sub-area III** (OEIC-WC): Optoelectronic integrated wavelength converter with monitoring function capabilities.

**Significant Achievements:** In this quarter, the following significant achievements were accomplished.

**Sub-Area I**

1. Delivery of third T-AOWC chip-on-carrier to MIT-LL.
2. Successful demonstration of world’s first monolithically integrated widely tunable all-optical wavelength converter operating error free at 10 Gbps with –2dBm input power sensitivity.
3. Wide tuning range operation for T-AOWC with 60 nm input and 32 nm output
4. First demonstration of two-stage wavelength converter demonstrating any wavelength input to any wavelength output using monolithic T-AOWC as second stage. Demonstrate 0 dB power penalty.
5. Investigation of the photocurrent assisted wavelength conversion effect.
6. Demonstration of photocurrent assisted AOWC EAM at 10 Gbit/s.
7. Demonstration of wavelength conversion with retiming and reshaping using the photocurrent assisted AOWC EAM.

**Sub-Area II**

8. Design and development of micro resonators compatible with both material and the fabrication process of tunable laser and wavelength converter. As a result resonator filters can be directly integrated with the rest of the chip.
9. Design, fabrication and characterization of very low loss TIR mirrors. Loss per mirror is less than 0.8 dB, which makes resonators based on TIR mirrors possible.
10. Fabrication and characterization micro resonators based on TIR mirrors.
11. Optimized Focused Ion Beam etching of TIR mirrors to achieve loss of ~ 1 dB/mirror
12. Achieved integrated fabrication of TIR mirrors, with internal LEDs to facilitate propagation and loss measurements.

14. First monolithically integrated directly-modulated OEIC wavelength converter. Successful conversion over ~20 nm output wavelengths at 2.5 Gbps, >90 dBHz^2/3 SFDR at 1 GHz. With wire-bonded hybrid: 2.5 Gbps conversion with ~2 dB power penalty over full wavelength range (>40 nm possible) and >90 dBHz^2/3 SFDR at 1 GHz.

15. Resonated wire-bonded hybrid (analog only): 105 dBHz^2/3 SFDR at 2.5 GHz for less than 0dBm input fiber-coupled optical power.

16. First monolithically integrated, MZ modulator-based OEIC wavelength converter. 1-2 dB power penalty over 37nm output wavelength range at 2.5 Gbps.

17. Successful completion of monolithically integrated EA modulator-based OEIC wavelength converter.
1. Program Management Plan

A program management plan for the baseline period is included as an Appendix in the form of Microsoft Project Gantt Chart identifying major tasks, milestones of the major tasks and their completion dates. A graphical representation of the budget for the first spending increment (FY03) is also included as an appendix to this quarterly report to the distribution list in the form of an excel graph showing the (1) monthly planned, committed and most recent actual spending, (2) cumulative spending (planned, committed and actual), and (3) cumulative total of money received from the government.

1.1. Program Plan Progress Summary

The status of our CS-WDM project milestones during the last quarter is reflected Table 1. The completed tasks are indicated with gray shading.

<table>
<thead>
<tr>
<th>Sub-Task</th>
<th>Description</th>
<th>Due Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Widely Tunable AOWC</td>
<td>Development of growth and processing technologies to fabricate integrated MZI-WC with tunable laser using offset quantum well design for active/passive waveguide fabrication</td>
<td>1/31/03</td>
<td>Completed 12/5/02</td>
</tr>
<tr>
<td>Widely Tunable AOWC</td>
<td>Report details of integration process and process characterization</td>
<td>2/3/03</td>
<td>Completed 2/3/03</td>
</tr>
<tr>
<td>Widely Tunable AOWC</td>
<td>Mask fabrication, device processing and mounting</td>
<td>4/21/03</td>
<td>Completed 3/15/03</td>
</tr>
<tr>
<td>Widely Tunable AOWC</td>
<td>Digital characterization</td>
<td>9/1/03</td>
<td>Completed 5/1/03</td>
</tr>
<tr>
<td>Widely Tunable AOWC</td>
<td>Analog characterization</td>
<td>9/1/03</td>
<td>Completed 9/1/03</td>
</tr>
<tr>
<td>EAM AOWC with signal monitoring</td>
<td>Initial demonstration</td>
<td>Not specified</td>
<td>Completed 4/25/03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task II</th>
<th>Description</th>
<th>Due Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP Ring Resonator: Coupled Disk Design</td>
<td>Development of growth and processing technologies to fabricate disk resonator filter compatible with in-Plane SOA-WC</td>
<td>9/20/02</td>
<td>Completed 12/1/02</td>
</tr>
<tr>
<td>InP Ring Resonator: Coupled Disk Design</td>
<td>Mask fabrication, device processing, mounting and AR coating</td>
<td>12/13/02</td>
<td>Completed 12/13/02</td>
</tr>
<tr>
<td>InP Ring Resonator: Coupled Disk Design</td>
<td>Fabricate and test small resonators</td>
<td>3/25/03</td>
<td>Completed: Disk Filter Completed, redesigned as TIR based filter based</td>
</tr>
<tr>
<td>InP Ring Resonator: TIR Design</td>
<td>Designed and fabricated first generation structures for wavelength selective devices</td>
<td>6/17/03</td>
<td>Completed 9/1/03</td>
</tr>
<tr>
<td>InP Ring Resonator Filter</td>
<td>Analog and Digital Performance Evaluation</td>
<td>8/29/03</td>
<td>In Progress.</td>
</tr>
<tr>
<td>InP TIR Mirror</td>
<td>Development of growth and processing technologies to fabricate strongly guiding waveguides and mirrors</td>
<td>9/20/02</td>
<td>Completed 12/1/02</td>
</tr>
<tr>
<td>InP TIR Mirror</td>
<td>Mask fabrication, device processing</td>
<td>1/31/03</td>
<td>Completed 12/1/02</td>
</tr>
<tr>
<td>InP TIR Mirror</td>
<td>Fabricate and test TIR mirrors</td>
<td>3/31/03</td>
<td>Completed 4/25/03</td>
</tr>
<tr>
<td>InP TIR Mirror</td>
<td>Fabricate and test multiple TIR mirrors with integrated InP waveguides on a single chip</td>
<td>8/29/03</td>
<td>Completed 9/15/03</td>
</tr>
<tr>
<td>InP TIR Mirror</td>
<td>Demonstrate TIR mirrors with integrated waveguides on single chip as platform for next generation AOWC devices</td>
<td>8/29/03</td>
<td>Completed 9/15/03</td>
</tr>
<tr>
<td>Task: Directly Modulated OEIC-WC</td>
<td>Develop growth and processing technologies to fabricate integrated PICs with tunable laser</td>
<td>12/13/02</td>
<td>Completed 11/2/02</td>
</tr>
<tr>
<td>Task: Directly Modulated OEIC-WC</td>
<td>Device fabrication and basic characterization of directly modulated OEIC wavelength converter</td>
<td>5/2/03</td>
<td>Completed 5/30/03</td>
</tr>
<tr>
<td>Task: Design PD/EAM with no Interface Electronics</td>
<td>Study and assess alternative SOA and detector designs for the directly modulated</td>
<td>12/13/02</td>
<td>Completed 12/10/02</td>
</tr>
<tr>
<td>Task: Design PD/EAM with no Interface Electronics</td>
<td>Study and evaluate saturable absorber and gain levered direct modulated devices</td>
<td>12/31/02</td>
<td>Completed 10/15/02</td>
</tr>
<tr>
<td>Task: Design PD/EAM with no Interface Electronics</td>
<td>Design and simulate various embodiments of PD/EAM modulated wavelength converters</td>
<td>8/29/03</td>
<td>Completed 9/1/03</td>
</tr>
</tbody>
</table>
1.2. Task I: All Optical Tunable Wavelength Converter

1.2.1. Digital Chirp Measurements

For time resolved chirp measurements, the T-AOWC MZI’s bias currents were optimized for maximum extinction ration in either inverting or non-inverting mode of operation at 2.5Gb/s. The output of the device was optically filtered and then led into an optical chirp test instrument. The interferometric method used for chirp measurement is based frequency and amplitude change measurements on two different slopes of the interferometer in order to obtain time resolved frequency change. The optical output from this instrument was connected to a high-speed digital oscilloscope, which is used in combination to perform measurements on the data pattern.

Time-resolved chirp was measured as a function of the input wavelength, output wavelength (set by the integrated on-chip laser) and interferometer bias point (inverting, non-inverting and in between). Example of results measured for non-inverting and inverting mode of operation is shown in Figure 1.

![Figure 1. Time resolved chirp measurement results](image)

Little input-output wavelength dependence of chirp parameter values was observed across the entire data set. chirp parameter value and sign depend on the slope of the transfer function of the wavelength converter in the selected regime of operation. For non-inverting operation, the average chirp parameter was measured to be -2 for 40nm input and 22 nm output wavelength range. For inverting mode of operation, the average chirp parameter was measured to be 1-3 for the same output wavelength range. Thus, the performance of the wavelength converter in transmission should consistently reduce the dispersion power penalty if operated in the suitable mode of operation (based on the fiber dispersion parameter). The chirp parameter sign measured
is consistent with theoretical predictions and previous results for an XPM-SOA based wavelength converter.

1.2.2. Regenerative Properties and Dynamic Range of the Wavelength Converter

Regenerative properties of the SOA-MZI based wavelength converters are based on their highly nonlinear optical transfer characteristics, as shown in Figure 2. To quantify the regenerative properties of the wavelength converter, the extinction ratio of the input signal was degraded in a controllable manner by adjusting the bias and the polarization of the light in the electrooptic modulator used to encode the data. The power level of the input signal was kept constant for all values of the input extinction ratio. Significant improvement in the output extinction ratio was measured – for input ER of 6.33 dB, the converted signal had an extinction of 12.06 dB in the non-inverting and 12.33 dB in the inverting mode of operation.

![Figure 2. Regenerative properties and dynamic range of the tunable wavelength converter](image)

However, decreasing the extinction of the input signal increases the average input power into the common SOA in the MZI, reducing the number of carriers and the gain of the laser signal, and thereby making it less sensitive to the optical power variation. Therefore, 6 dBm of input optical power results in only -4.4 dBm of the output optical power. On the other hand, device excitation with the high ER signal at the input (12 dB) will result in the conversion gain of around 2 dB, with -4dBm at the optical input producing -2dBm in the converted signal.

Dynamic range of operation can be controlled by the input SOA bias, as well as the bias set-point of the MZI. Figure 2a shows maximum ER values measured as a function of the data input power. High extinction ratio, greater than 10 dB, can be maintained over 16 dB of input signal power variation. Figure 2b shows the converted eye for -6dBm input power in fiber, corresponding to the WC output power of -4dB in fiber. The dynamic range is limited by the passive losses and available gain of the input SOA.

1.2.3. Digital and Analog Wavelength Routing Demonstrations

For this experiment, the transmitter consisted of a tunable laser operating at 1555nm, a polarization controller, and a lithium niobate electro-optic modulator. An EDFA was placed after the transmitter to amplify the signal for transmission through 50km of dispersion shifted Truewave fiber and a polarization controller was placed before the device to maximize interaction of the incident light with the active regions of the device. Two conical-tipped lensed
fibers on piezo-controlled translational stages were used to couple light into and out of the device. Four wavelengths (1551.9nm, 1558.6nm, 1560.0nm, 1561.6nm), each corresponding to a different port on the AWGR, were chosen for their placement in the c-band and for their relation to the input wavelength of 1555nm. Tuning of the device’s output wavelength was achieved by current injection through the front and back mirror sections of the integrated SG-DBR laser.

For the experimental demonstration, the data was generated using a BERT with $2^{31} - 1$ PRBS data at 2.5 Gb/s. The optical power measured in fiber at the input to the device was -2.5 dBm. For each output wavelength, the currents injected through the SOAs of the device’s MZI arms were adjusted to maximize the extinction ratio of the wavelength-converted signal. The extinction ratio was calculated using the eye diagram by an oscilloscope, and extinction ratios of 13dB or greater were measured for each of the wavelength converted signals. BER measurements were taken after the transmitter, after the 50km spool of fiber, and at the output ports of the AWGR for each wavelength using an optically pre-amplified receiver whose sensitivity was -34.5 dBm. Results of the BER measurements are shown in Figure 3. Less than 1dB of power penalty was measured at a bit-error rate of $10^{-9}$ for each of the wavelength converted signals.

![Figure 3. BER results and system schematic of the digital wavelength routing experiment](image-url)
For the second part of the experiment, two frequency tones were used to drive a Mach-Zehnder modulator, the signal was transmitted through 50 km of fiber, wavelength converted, routed through an AWG and the SFDR of the resulting signal was measured. The system setup and results of these measurements are shown in Figure 4.

![System diagram and results of the analog wavelength routing experiment](image)

**Figure 4.** System diagram and results of the analog wavelength routing experiment

**1.2.4. Protection Switching**

A reliable fiber optic system must be capable of providing an alternative pathway for communication should a link of fiber become damaged or broken. One method of offering such link protection has been demonstrated with a TA-OWC using the experimental setup shown in Figure 5.

![Experimental setup for the protection switching experiment](image)

**Figure 5.** Experimental setup for the protection switching experiment

For this demonstration, a 1550nm signal is initially sent through one of two 50km spools of fiber that are connected to the transmitting and receiving ends via two electro-mechanical switches. The power at the receiving end of the first spool (Fiber #1) is detected through a 2% tap by a power meter, which is monitored by a computer running a data acquisition loop in LabView. A fiber fault is simulated by disconnecting Fiber #1 from Switch #1. The subsequent loss in power triggers the software to exit the acquisition loop and protect the link. Protection is
achieved by tuning the transmitter wavelength (1555nm) and switching the electro-mechanical switches to the second spool of fiber (Fiber #2). A T-AOWC converts all signals at the receiving end, before and after protection, to 1565nm.

The transmitter consists of a tunable laser, a polarization controller, and a lithium niobate electro-optic modulator. An EDFA was placed after the transmitter to amplify the signal for transmission through two Agilent 86060C Lightwave Switches and one of two parallel 50km spools of dispersion shifted Truewave fiber. An EDFA and an attenuator were placed after the second switch to, respectively, amplify and finely control the signal power for wavelength conversion. A polarization controller was placed before the T-AOWC to maximize interaction of the incident light with the active regions of the device. Two conical-tipped lensed-fibers on piezo-controlled translational stages were used to couple light into and out of the T-AOWC. The temperature of the device was kept at 18°C using a thermoelectric cooler.

For the experimental demonstration, the data was generated using a BERT with $2^{31} - 1$ PRBS data at 2.5 Gb/s. The optical power measured at the input to the device was -2.0 dBm, with an additional 4dB of estimated coupling loss from the tapered fiber to the on-chip waveguide. For the initial input wavelength of 1550nm, the currents injected through the SOAs of the TA-OWC’s MZI arms were adjusted to maximize the extinction ratio of the wavelength converted signal. For the protection input wavelength of 1555nm, the operating conditions of the TA-OWC remained the same. The extinction ratio was calculated using the eye diagram by an oscilloscope, and extinction ratios of 13dB or greater were measured for the wavelength converted signal both before and after protection switching. The eye diagrams of the wavelength converted signals are shown as insets in Figure 6. To large time scale oscilloscope readout during protection switching is shown below the eye diagrams. A switching speed of 1 second was observed, and is limited in this experiment by the speed of the electro-mechanical switches, the tuning speed of the transmitter, and the speed of power meter measurements using LabView over GPIB.

![Figure 6.](image)  
*(Black and white) Long time scale oscilloscope readout of wavelength converted signal during protection switching*
1.2.5. 2-stage Wavelength Conversion Experiment Using the Monolithically Integrated Tunable Wavelength Converter

One of the outbound goals of this project is to monolithically integrate a novel two-stage T-AOWC. There are many performance advantages to this approach. In this quarter we have used the integrated 2nd stage T-AOWC with a discrete 1st stage AOWC to demonstrate the advantages and performance of this approach.

The wavelength converter shown in Figure 7 consists of two stages. The first stage utilizes the XGM effect in an SOA to perform wavelength conversion from any input wavelength $\lambda_{in}$ to a fixed internal wavelength $\lambda_{int}$ via down conversion, which is the optimal type of conversion for XGM in SOAs. The polarization state and intermediate wavelength can be optimized for conversion in the second stage. The second stage consists of an InP SGDBR laser integrated with an SOA-MZI WC. Incoming data at the fixed wavelength $\lambda_{int}$ enters the chip through an input amplifier and is combined with CW light from the on-chip SGDBR laser in one branch of the interferometer. This induces XPM of the SGDBR generated light, transcribing the data to the new wavelength, $\lambda_{out}$ set by the integrated laser.

![Figure 7. Setup of the 2-stage wavelength converter](image)

Performance through the 2-stage WC was characterized at 2.5 Gbps. The input electro-optic modulator in the transmitter was biased to provide highest extinction. The first-stage SOA was biased at 133 mA and driven in saturation to effect XGM. The input wavelength was 1565 nm at a power of 8.8 dBm and further amplified by an EDFA. The internal wavelength was 1555 nm at a power of -10 dBm. Both wavelengths were coupled together and sent through the first-stage SOA and an optical bandpass filter centered at $\lambda_{int}$ to filter the converted signal and reject the input wavelength. The data at the internal wavelength was then subsequently sent through an EDFA and the integrated wavelength converter. The input wavelength range into the TAO-WC spans 50 nm, covering both C and L bands, while the output wavelength from the SGDBR laser on the integrated WC can be tuned over 22 nm in the L-band and was set to 1573 nm, with a maximum output power of 4 dBm. The TAO-WC MZI’s bias currents were optimized for maximum extinction ratio in the inverting mode of operation. The wavelength converted signal from the TAO-WC was filtered with a 1.2 nm optical BPF and the internal wavelength was rejected. BER measurements were performed on the XGM and XPM wavelength-converted signal and are shown in Figure 8. Receiver sensitivity of -17 dBm was achieved without optical
preamplification in the receiver. The 2.5 dB power penalty due to XGM can be attributed to the reduced extinction and addition of ASE noise from the SOA. Measured eye diagrams are also included illustrating the extinction ratio degradation of the XGM process as well as extinction ratio and noise improvement of the 2-stage process.

![Figure 8. BER measurement and eye diagrams for each stage of wavelength conversion](image)

Regeneration in the XPM stage is due to the nonlinear transfer function of the T-AOWC, as seen in Figure 9 for the inverting mode of operation. The high slope of the transfer function improves the ER from 10.7 dB after the XGM stage to 17.7 dB after the XPM stage. The extinction ratio of the device can be improved further by decoupling the phase and gain control in each arm of the MZI. Nonlinear thresholding of the incoming data also provides noise suppression and improves SNR.

![Figure 9. T-AOWC nonlinear transfer function](image)

### 1.2.6. New Generation Single-Stage Integrated Widely Tunable Sampled-Grating DBR Tunable Laser and SOA Based Mach Zehnder Wavelength Converter

We have successfully fabricated the first batch of fully operational tunable wavelength converters and conducted digital performance characterization and preliminary analog testing. Comprehensive characterization was conducted on two device types: S-bend Mach-Zehnder Interferometer (MZI-AOWC) and MMI-MZI-AOWC. The main difference in performance
between these two device types was higher output power of the MZI-AOWC device (up to 5dBm).

The laser is 1.5mm long and has five sections: front mirror, gain section, phase section, back mirror and back facet detector. The mirror design was improved in order to provide for wider tuning range of 40nm.

The interferometer branches are defined by two S-bends and 1.5 mm long SOAs. The output light of the SGDBR laser is equally split using a 1x2 multimode interference (MMI) based light splitter, and then amplified by 2 in-line SOAs that also serve as part of the interferometer S bends. This amplified light is then coupled with light from the input waveguides using 2x1 MMI combiners into the SOAs in the branches of the MZI. 1.5 mm long MZI SOAs are used to achieve 10 Gbps operation. Each branch of the MZI has a 100_m long passive section contacted by a metal pad which is used to adjust the relative phase of the MZI independently of the SOA bias current. This separation of phase control provides for easier optimization of the operating bias point of the wavelength converter as well as better extinction for both inverting and non-inverting modes of operation.

The branches of the MZI are coupled by a MMI based 2x2 coupler at the output. Depending on the relative phase of the MZI branches, the output light will be split between the two output waveguides with two extreme cases: for the phase difference of -90 deg, all of the light will be coming out of one waveguide whereas for the phase difference of +90 deg, all of the light will be coming out of the other waveguide. The two outputs are used to constantly remove the light from the chip (this is different from our previous design), which helps prevent light resonance buildup. Both of the output waveguides are curved and tapered before they reach the facet in order to minimize the back reflections.

The input signal is coupled onto the chip through a tapered, angled input waveguide, and then amplified by 2 SOAs running alongside the laser. In order to reduce the thermal crosstalk, the input SOAs are about 200 μm away laterally from the SGDBR active regions. The total chip size is 0.5x5.3mm. This device is fabricated using our standard MOCVD grown offset quantum well integration platform. However, the waveguide composition is changed relative to the previous device generation to 1.4Q in order to reduce the absorptive waveguide losses.

1.2.7. Static and Digital Performance Results

Some of the major limitations in performance of the first generation of devices are a consequence of relative low input power into the Mach-Zehnder interferometer, and the need to control the phase of the light by changing the bias currents of the SOAs in the branches of the interferometer. The generation 2 device (Gen-2) removes these constraints on operation of the wavelength converter and is shown in Figure 10.

There are several key changes to the design that have been implemented in the Gen-2 device including

1) Independent phase electrodes in the branches of the MZI
2) Longer SOAs in the MZI
3) Dual output waveguide with signal monitoring capability
4) Output SOAs after the SGDBR laser
5) Differential input waveguides
The ability to control the phase in the interferometer independently (1) and longer SOAs (2) will lead to higher extinction since the arms of the interferometer will be balanced. Ultimately, this will lead to higher output power of the device. The output power will also be improved by the lower loss waveguide layer that we have incorporated into our base structure.

The output SOAs after the SGDBR laser help increase the level of saturation of the SOAs in the MZI, thereby decreasing the carrier lifetime, which enabled error-free wavelength conversion at 10 Gbps NRZ for this device set. Higher output power should further reduce the RIN and improve the SFDR of the device. The dual output from the interferometer allows for light evacuation from the chip at all times, plus it provides us with an option to do electrical signal monitoring without sacrificing the device performance. Finally, having two functional input waveguides and SOAs provides for redundancy and also enables additional device characterization by using a differential excitation to the interferometer, such as RZ wavelength conversion.

For testing performed, the input signal at 1570nm was externally modulated with NRZ 2^31-1 PRBS data at both 2.5 and 10 Gbps. Light was coupled into and out of the device using conically-tapered lensed fiber. The converted output wavelength was filtered using a thin-film tunable filter and detected with an Agilent 83434A 10Gb/s lightwave receiver. For non-inverting mode of operation, both of the SOAs are biased by equal electrical currents, and the relative phase of the two branches is adjusted using the phase electrodes to cancel out the two signals. As can be seen in Figure 11a, it takes about 5 mA to turn the interferometer off completely; therefore, the new method of phase control is very efficient. For inverting mode of operation, the MZI-SOA bias needs to be adjusted in such a way that the powers of the CW signals in the MZI branches are equal for maximum input power of the data stream. Representative tuning of the device to 4 different output wavelengths over a 35nm tuning range is shown in Figure 11b and these are the same wavelengths used in the BER measurements.
The measured BER curves are shown in Figure 12. The data input power was only -10dBm at 2.5Gbps and -5dBm at 10Gbps. The average output power of the wavelength converter was around 0dBm. At 2.5 Gbps the maximum power penalty measured was 0.8dB which can be attributed mainly to the ASE noise generated by on-chip SOAs. At 10Gbps, the power penalty was measured as low as 1.4dB for output wavelengths between 1542-1555nm. The penalty increased to around 3dB, and the BER slope decreased for longer wavelengths (above 1570nm), which can be attributed to SNR and extinction ratio degradation for wavelengths near the band edge. We expect that these numbers could improve with future device designs.

The development of low voltage modulators (0.35 V) has enabled the demonstration of AOWC using the photocurrent generated in an EAM. This photocurrent assisted wavelength (PAW) converter is compact and requires quite low input optical power. The concept was proposed in the last quarterly report and the performance was investigated here. The configuration of PAW-Conversion is shown in Figure 13. The TW-EAM is designed with traveling-wave electrodes (CPW line) and has a 300µm active waveguide. The pump is absorbed within a short distance near the input facet and generates a photocurrent signal propagating in both directions of the CPW line. The co-propagating part of the photocurrent signal travels through the rest of the active waveguide and changes the local voltage and hence the absorption experienced by the probe. The photocurrent signal finally reaches port 1 and can be detected by an outside circuit to provide electrical monitoring. On the other hand, the counter-propagating part of the photocurrent signal goes to the termination at port 2. If the termination is 50 Ohm, the photocurrent signal is terminated. However, it will be reflected and becomes co-propagating if the termination is an open. The probe is selected after the conversion with a 2.4 nm filter.

![PAW Wavelength Converter Diagram](image)

Figure 13. PAW Wavelength Converter

Figure 14 shows the eye diagrams of the electrical signal from port 1 and the converted optical signal. Pump is 13 dBm at 1545.8 nm and probe is 1 dBm CW at 1555.2 nm. The electrical eye amplitude with open termination is doubled compared to that with 50 Ohm termination, due to the reflection at port 2. As a result, its corresponding optical eye is larger and has a higher extinction ratio (10.9dB v.s. 7.5dB) which results in a lower power penalty (0.5 dB v.s. 1.5 dB) as shown in Fig. 3(a). It can be inferred that the saturation mechanism contributes 4.1dB (10.9-(10.9-7.5)*2) of extinction ratio and the photocurrent-assisted mechanism contributed to 6.8dB (10.9-4.1) for the open termination and 3.4dB (7.5-4.1) for the 50 Ohm termination. It is evident that the photocurrent-assisted mechanism can contribute more than the saturation mechanism. The electrical signal from port 1 can be fed into the BERT directly and no error was detected. The pump power is lowered to measure the BER curves and the open has a better receiver sensitivity because of its larger eye amplitude. Note that the pumping power required for NRZ conversion using PAW-Conversion is comparable to that required for RZ conversion with 10% pulselwidth using lumped-EAM utilizing only saturation mechanism. This would suggest a 10 dB higher pumping power if the NRZ conversion were carried out with a lumped-EAM.
1.2.4 PAW-Conversion with RF-drive

To reduce the effect of long fall time on RZ data, an RF-driven approach is adopted where a synchronized 10 GHz sinusoidal RF is fed into the TW-EAM through a power divider which reduces back-reflection from the amplifier and also provides electrical monitoring for the open termination. This approach was originally proposed to re-shape the converted RZ signal in conventional EAM-based wavelength converter because the applied RF-drive can increase the bias voltage momentarily to reduce the carrier sweep-out time provided the phase is adjusted properly. Consequently, the tails of the converted RZ signal can be trimmed.

When applied with PAW-Conversion, the RF-drive not only increases the bias voltage momentarily but also mixes with the photocurrent signal. Therefore, the trimming effect is further enhanced through the nonlinear E-O transfer function and the shape of the converted signal is mainly determined by the RF-drive because of its stronger magnitude. Error! Reference source not found. shows the eye diagrams. The electrical eye is a combination of photocurrent signal and the applied RF-drive. BER measurement of these electrical signals is possible given a matched low-pass filter to remove the strong 10 GHz tone. The converted optical RZ eyes are well shaped and has less noise due to an improved carrier sweep-out time which reduces the intersymbol interference (ISI) caused by the long tails. The bias voltages are adjusted to minimize the power penalty. The power penalty is 1.0 dB with 50 Ohm termination and 1.8 dB with open termination. The higher penalty for the open termination is caused by the multiple reflections between the open and the amplifier. The 1.0 dB penalty for the 50 Ohm can be attributed to the finite extinction ratio, residue ISI, and also some reflections from the amplifier.

1.2.5. Re-timing and Re-shaping Capabilities

RF-driven PAW-Conversion can have re-timing and re-shaping capabilities. To evaluate re-timing of the converted signal, the pulse train in the transmitter is FM modulated but the 10 GHz RF-drive to the TW-EAM remains pure which can also be a recovered clock. The FM
modulation index is 0.3 that corresponds to +/- 4.8 ps\textsubscript{pp} of jitter. The standard deviation measured with the sampling scope is 3.5 ps but after the conversion it is reduced to 1.8 ps. However, there is still a 1.2 dB of power penalty caused by other effects as stated above. As shown in Figure 15a, RF-driven PAW-Conversion can consistently reduce the timing jitter by half up to a FM modulation index of 0.6. The first side-band suppression ratio of the FM modulation can also be reduced by 10 dB after conversion. Re-shaping capability is also demonstrated in Figure 15, where the pump pulse is intentionally broadened to 30 ps but the average power is still 13 dBm. The converted signal has a reduced pulsewidth of 12 ps, which is determined by the RF-drive.

\begin{center}
\includegraphics[width=0.5\textwidth]{fig15}
\end{center}

\textit{Figure 15.} Re-timing results

1.3. Task II: Filter/Mux/Router

This sub-area addresses the process compatible design and fabrication of optical filters and TIR mirrors and waveguides for the AWOC chip-scale project. The results of this research will be used in the AOWC in Phase II of this project.

1.3.1. TIR and Disc Micro-resonator Filters Compatible with InP Planar Integration Platform

In our previous report period we continued our work on micro resonator filters. We fabricated total internal reflection (TIR) mirrors and several types of traveling wave resonators. The progress for both tasks is described below.

**TIR mirrors**

Figure 16 shows the TIR mirror arrangement used in the characterization along with the photograph of fabricated TIR mirrors. In the photograph the darkest areas are the optical waveguides and the white areas are the deeply etched regions. The mirrors are fabricated using a self aligned process. The waveguide and mirror features are defined using the same mask in one step. The fabrication is completed using two etching steps, one for the waveguide fabrication, which also partially etches the mirrors and the other for the mirror etch. The close up view of the mirrors aligned to waveguides in a resonator is shown. Comparing the loss through a set of TIR mirrors with the loss of a straight waveguide, we can measure the additional loss due to TIR mirrors. The result of this measurement is shown in Figure 17. The result indicates that additional loss per mirror is 0.71± 0.06 dB. Such a low loss is due to proper design of the mirror and the very smooth low damage RIE etch. Such low mirror loss also makes resonators based on mirrors possible.
Traveling wave resonators

We also fabricated different types of traveling wave resonators. Figure 18 shows the different types of resonators fabricated. The quadrant at the top left shows the top view of a TIR mirror resonator and a micro disk resonator. The other quadrants show the details of two different types of TIR mirror resonators and a micro disk resonator. For clarity these photos do not show the contact pads. All these resonators have the same material design as the tunable laser and the wavelength converters. Furthermore, the fabrication process is the same as other device processing except for the deep etch required for TIR mirrors and micro disks. Hence they can be directly integrated on the same chip with tunable laser and the wavelength converters. Figure 19 shows the details of TIR mirror and micro disk resonators.
Figure 18. Different types of resonators fabricated.

Figure 19. Photographs of TIR mirror and micro disk resonators after the deep etch.

We are also characterizing such resonators. Figure 20 shows the transmission through a passive waveguide attached to a 100 μm TIR mirror resonator at four different current levels. We see periodic transmission dips superimposed with various resonances. As the current applied to the active region inside the resonator increases the resonances first become more pronounced
as we approach the critical coupling condition. For this device critical coupling is achieved around 20 mA. Further increase in the current drives the resonator away from critical coupling. There is also a slight change in the resonance wavelength due to change in the refractive index. In these measurements the facets were not AR coated. This creates spurious resonances and composite cavity effects, which interfere with the resonances due to the actual resonator. This fact made the characterization of shorter resonators more difficult. In some cases it is not possible to clearly identify the resonances due to the resonator itself. At the present time we are trying to AR coat the facets to make more accurate measurements. This is a challenging task, since we need broadband coatings.

![Wavelength vs Transmission](image)

**Figure 20.** Transmission through a large TIR mirror resonator at different currents. Mirror schematic is also shown in the right side of figure.

### 1.3.2. Low Loss TIR Mirrors and Waveguides for InP Planar Integration Platform

In this work we investigate techniques to increase the density of PIC circuits in our InP integration platform in order to reduce the area of chip-scale AOWCs, filters and mux/demuxes. Our approach is to fabricate large angle bending by total internal reflective (TIR) mirrors. This approach has the potential to be low cost. We focus on a compatible process that can be integrated with our existing InGaAs/InP Chip-scale WDM devices.

Figure 21 illustrates the basic TIR mirror structure that we have demonstrated which has been discussed in previous reports. The challenge in producing low loss TIR mirrors involves (i) formation of sufficiently smooth mirrors with a vertical profile, oriented at the correct angle, and (ii) developing a process that is compatible with the AOWC chip scale circuit so that these mirrors may be employed for certain functions. Our current goal is for 0.5dB loss per mirror. In this recent quarter, we have improved the Focused Ion Beam (FIB) fabrication techniques to achieve ~ 1 dB loss per mirror.
We have optimized FIB parameters such as beam current, beam dwell time, and beam overlap, to achieve smooth TIR mirror surfaces, with vertical profiles. Figure 22 shows the TIR mirror region before and after processing with the FIB.

To evaluate the mirror losses, we designed and fabricated the following photonic integrated circuit, shown in Figure 23. The center is the LED structure; by applying forward voltage bias, the integrated, on-chip LED will couple into both the left and right side waveguides. Along the right-side waveguide paths, we have 2, 4, 6, or 8 TIR mirrors. The fabrication process is fully compatible with the InP active/passive planar platform.

The schematic measurement setup is illustrated in Figure 24. When the LED is turned on, we can measure the light output from both sides of the waveguide by lens fiber.
By comparing the losses by 2, 4, 6 mirrors, we find the mirror losses roughly follows a linear trend. From the following simple plot in Figure 25, we can extract the slope of the curve, which is approximately 1.06dB/mirror.

Mask redesign, continued FIB optimization, and elimination of other scattering losses (such as losses through the substrate) should allow us to achieve truly low-loss TIR mirrors, with a process that has the flexibility to be readily integrated within the full chip-scale process.

1.4. Task III: OEOIC-WC

1.4.1. Directly Modulated SGDBR Wavelength Converters

Monolithically integrated wavelength converters:

Last quarter, the analog performance of the first generation OEIC wavelength converters was presented with additional initial data of the digital performance. This quarter, the digital performance has been more carefully investigated. These first generation chips suffered from large series resistance due to an error in fabrication. A second hybrid integration approach, involving an input SOA-detector stage and an output directly-modulated laser stage selected from separate chips, connected by a wirebond has also been tested for digital and analog performance. This approach has given improved results thanks to the higher performance of the individual components involved. A resonant tradeoff between bandwidth and conversion gain
has also been investigated, mainly in order to demonstrate potential improvements in terms of analog conversion gain and linearity. Finally, further work involving directly-modulated OEIC wavelength converters are being summarized.

Figure 26 shows detected eye diagrams for different output wavelengths after wavelength conversion for the integrated OEIC wavelength converter. Some degradation in eye opening can be seen at higher wavelengths. This is confirmed by the decreasing slope in Figure 27, where the detected bit error rate (BER) is plotted against received optical power. Error-free operation (BER<10⁻⁹) has been obtained for all four investigated output wavelengths. The power penalty compared to back-to-back configuration without wavelength conversion, is between 5dB to 7dB.

![Figure 26](image)

**Figure 26.** Converted, detected and filtered eye diagrams for different output wavelengths and 1548nm input wavelength from first generation chip.

![Figure 27](image)

**Figure 27.** Detected BER as a function of received optical power for different input wavelengths and 1548 nm input wavelength.

Figure 27 on the right hand side shows the BER as a function of gain section bias at 1551nm output wavelength. This plot illustrates well the limits to the available BER penalty. As the gain section bias point decreases, the performance improves due to improved extinction ratio. Below 51mA, some performance degradation appears due to limited direct modulation bandwidth. The power penalty corresponds well to the observed extinction ratio, currently on the order of only 2dB. There are two paths to improved extinction ratio: higher generated photocurrent and improving direct modulation response at low gain section bias current. Lowering the serial diode resistance on the chip (currently high) is expected to both improve direct modulation response and improve SOA preamplifier gain, leading to higher generated photocurrent.

The signal monitoring function has also been further characterized. Figure 28 shows the BER, detected from the voltage swing over the gain section of the laser as a function of fiber-coupled input optical power. The required input power for successful signal monitoring is an
order of magnitude lower than required for successful wavelength conversion. Figure 28 also shows the corresponding detected eye for error-free monitoring.

![Figure 28](image)

**Figure 28.** (Left Figure) Detected BER as a function of received optical power for signal monitoring function and 1548 nm input wavelength. (Right Figure) Detected signal monitor eye diagram at 1548 nm input wavelength.

The photodetector shows similar characteristics over a wide input wavelength range. The performance varying the input wavelength sensitivity is determined by the characteristics of the source of the optical input signal. The output wavelength range is lower than the input wavelength range. The output wavelength can be tuned to three-quarters of the 40 - 100GHz-spaced channels over a 32nm wavelength range, as shown Figure 29.

![Figure 29](image)

**Figure 29.** Achieved sidemode suppression ratio for 40 - 100GHz-spaced channels over 32nm wavelength range.

**Hybrid integrated detector- laser configuration:**

In order to investigate the potential performance of the directly-modulated OEIC wavelength converter approach, an alternative approach of using input and output stages selected from different chips was investigated. The two chips were both mounted on a common AlN-subcarrier and connected by a wirebond. By using this approach, high-performance components were chosen for overall improved results. As shown by Figure 30, the maximum 3-dB conversion bandwidth is increased to about 6 GHz at 120mA. Conversion gain approaching unity can also be achieved, as shown by Figure 30, where also the SFDR is shown, both as a function of gain section bias. The SFDR performance shows no improvement compared to the integrated version, still >90 dBHz$^{2/3}$, taken at 1GHz.
The real improvement is found in achieved extinction ratio, as illustrated by Figure 31. The extinction ratio and therefore the BER penalty improves with decreasing bias to 28 mA, where 8dB of extinction ratio results in only 2-dB power penalty for conversion from 1548 nm to 1551 nm. The required fiber-coupled input power is reduced by more than an order of magnitude to less than 2mW, mainly a result of increased gain of the preamplifier SOA. Figure 32 shows the corresponding received eye diagram for error-free wavelength conversion from 1552nm to 1555nm. Figure 32 also shows the BER performance, varying the output wavelength. More than 32 - 100GHz spaced channels were verified. SMSR better than 40dB can be achieved over 40nm quasi-continuous tuning range of the directly modulated laser.

Figure 30. (Left Figure) RF conversion frequency response for hybrid directly modulated wavelength converter configuration. (Right Figure) Conversion gain and SFDR at 1 GHz as a function of gain section bias.

Figure 31. Detected BER as a function of received optical power for different gain section bias points and 1548 nm input wavelength. Achieved conversion power penalty compared to back-to-back and corresponding extinction ratio.
Figure 32. Detected eye diagram corresponding to error-free conversion from 1552nm to 1555 nm. Fig. 12. Detected BER as a function of received optical power for different input wavelengths and 1548 nm input wavelength.

1.4.2. Monolithically Integrated External Modulator Wavelength Converters

EA modulated OEIC wavelength converters

Processing has been completed of the first generation wavelength converter devices of a second type in which photocurrent from a photodetector is used to directly drive an electro-absorption modulator (EAM) with enabled signal monitoring features. Initial testing of the tunable Sampled Grating DBR (SGDBR) Lasers is promising with threshold currents of ~40 mA, peak power of > 10 mW out (with 300 um Optical Amplifier), a tuning range of 40 nm centered around 1550 nm, and Side Mode Supression Ratio (SMSR) values of greater than 35 dB. Figure 33 shows preliminary LIV and course tuning spectra.

Figure 33. Output Power of an SGDBR Laser vs. Input Current for the Electroabsorption Modulator based OEIC wavelength Converter SGDBR Lasers. Right hand figure shows Course Tuning Spectra for the Electroabsorption Modulator based OEIC wavelength Converter SGDBR Lasers.

Experiments within the next several months will focus on advanced photodetector design, photodetector saturation power and bandwidth, EAM efficiency and bandwidth, EAM linearity, and wavelength converter linearity, bandwidth and overall efficiency. In addition, a comparison to earlier device bandwidth and efficiency simulation results will be performed for use as design improvements in future wavelength converter generations.
MZ modulated OEIC wavelength converters

This particular implementation uses a monolithically-integrated widely-tunable wavelength converter based on a SGDBR-SOA-MZ transmitter and integrated franz-keldysh photo-detector (TPD-MZ-WC) (Figure 34). The Mach-Zehnder design has high extinction with a very low drive voltage making it suitable as a driving modulator for the device (Figure 34). The modulation efficiency is high due to the large change in index and absorption in the branches of the waveguide (band-gap energy corresponds to $\lambda=1.4$.m).

The Mach-Zehnder modulator utilizes one 1x2 Multimode interference (MMI) coupler (97um long) at the input of the interferometer with curved waveguides extending to a separation of 20m in between the two branches and a 172m 2x2 MMI at the output of the MZ modulator section. The outputs are angled to reduce the AR coating requirements. The total device chip size is 1mm x 3.5mm. For the TPD-MZ-WC, the pads on both the bulk (Franz-Kelydsh) detector and the MZ are both 200m long. This bulk detector drives one of the branches of a SGDBR-SOA-MZ transmitter at the output wavelength $\lambda$. For improvement of the lumped bandwidth, a 50 ohm parallel resistor was connected between the MZ p-metal and ground contacts.

BER curves as a function of receiver power were generated using an experimental setup as shown in Figure 35. Also shown in Figure 35 are the BER measurements. The PBRS 2.5 Gbit/s output waveforms corresponded to 7.5-8.3 dB extinction across the wavelength range. Error free
wavelength conversion was achieved over a wide range (37nm output range) corresponding to a 1-2dB power penalty over this range. More than 32 – 100GHz spaced channels were verified. The device was biased with the following currents. Gain section = 120mA, SOA = 70mA, MZ branch1 (modulated) = -1V, MZ branch2 = -3.6V. The tuning was performed by current injection into the rear mirror.

1.5. Wafer Processing Subcontract (Agility Communications)

Agility has continued to support this program in its role as a subcontractor supplying 1) base epitaxial structures, 2) MOCVD regrowth and 3) facet coating. Such services allow the UCSB program to take full advantage of Agility’s high level of control on these critical growth and process steps.

2. Publications

The following publications have resulted to-date from this research project:


3. Programmatic Interactions and Collaborations

3.1. Test Facility: MIT Lincoln Labs

- Earlier this year, two students visited MIT-LL from UCSB for 7 days and helped perform detailed measurements on AOWC devices that were brought with them. This past quarter, a post-doc from UCSB visited MIT-LL and brought the remaining AOWC chip on carrier and the three OEIC chips on carrier to satisfy the deliverable and carry out experiments.

4. Patents

None to date.
5. Appendix A: Program Management Plan for Baseline Period

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Qtr 2, 2002</th>
<th>Qtr 3, 2002</th>
<th>Qtr 4, 2002</th>
<th>Qtr 1, 2003</th>
<th>Qtr 2, 2003</th>
<th>Qtr 3, 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In-Plane SOA Interferometric Wavelength Converter (AOWC): Task Leader: D. J. Blumenthal</td>
<td></td>
<td></td>
<td></td>
<td>1/31</td>
<td>1/31</td>
<td>1/31</td>
</tr>
<tr>
<td>2</td>
<td>Single Stage SOA-MZI/WC with integrated tunable laser and external filter</td>
<td></td>
<td></td>
<td></td>
<td>2/03</td>
<td>2/03</td>
<td>2/03</td>
</tr>
<tr>
<td>3</td>
<td>Development of growth and processing technologies to fabricate integrated MZI-WC with tunable laser using offset quantum well design for active/passive waveguide fabrication</td>
<td></td>
<td></td>
<td></td>
<td>3/14</td>
<td>3/14</td>
<td>3/14</td>
</tr>
<tr>
<td>5</td>
<td>Mask fabrication, device processing, mounting and AR coating</td>
<td></td>
<td></td>
<td></td>
<td>5/01</td>
<td>5/01</td>
<td>5/01</td>
</tr>
<tr>
<td>6</td>
<td>Digital and analog performance evaluation</td>
<td></td>
<td></td>
<td></td>
<td>6/04</td>
<td>6/04</td>
<td>6/04</td>
</tr>
<tr>
<td>7</td>
<td>Delivery of operational 32 wavelength single stage SOA/MZI to DARPA designated government or FFRDC test facility</td>
<td></td>
<td></td>
<td></td>
<td>7/10</td>
<td>7/10</td>
<td>7/10</td>
</tr>
<tr>
<td>8</td>
<td>Optical Filter/Filter/Router: Task Leader: N. Dagli</td>
<td></td>
<td></td>
<td></td>
<td>8/20</td>
<td>8/20</td>
<td>8/20</td>
</tr>
<tr>
<td>9</td>
<td>InP TIR Mirror</td>
<td></td>
<td></td>
<td></td>
<td>9/23</td>
<td>9/23</td>
<td>9/23</td>
</tr>
<tr>
<td>10</td>
<td>Development of growth and processing technologies to fabricate strongly guiding waveguides and TIR mirrors</td>
<td></td>
<td></td>
<td></td>
<td>10/15</td>
<td>10/15</td>
<td>10/15</td>
</tr>
<tr>
<td>11</td>
<td>Mask fabrication, device processing</td>
<td></td>
<td></td>
<td></td>
<td>11/12</td>
<td>11/12</td>
<td>11/12</td>
</tr>
<tr>
<td>12</td>
<td>Fabricate and test TIR mirrors</td>
<td></td>
<td></td>
<td></td>
<td>12/10</td>
<td>12/10</td>
<td>12/10</td>
</tr>
<tr>
<td>13</td>
<td>Design and Fabrication Larger Devices with Wavelength Selective Coupling</td>
<td></td>
<td></td>
<td></td>
<td>13/17</td>
<td>13/17</td>
<td>13/17</td>
</tr>
<tr>
<td>14</td>
<td>Test Larger Wavelength Selective Coupled Devices</td>
<td></td>
<td></td>
<td></td>
<td>14/15</td>
<td>14/15</td>
<td>14/15</td>
</tr>
<tr>
<td>15</td>
<td>Design and analog performance evaluation</td>
<td></td>
<td></td>
<td></td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
</tr>
<tr>
<td>16</td>
<td>Demonstrate InP single disk resonator filter with 100 GHz FSR including measurements of 512, NF</td>
<td></td>
<td></td>
<td></td>
<td>16/09</td>
<td>16/09</td>
<td>16/09</td>
</tr>
<tr>
<td>17</td>
<td>InP TIR Mirror</td>
<td></td>
<td></td>
<td></td>
<td>17/09</td>
<td>17/09</td>
<td>17/09</td>
</tr>
<tr>
<td>18</td>
<td>Development of growth and processing technologies to fabricate strongly guiding waveguides and TIR mirrors</td>
<td></td>
<td></td>
<td></td>
<td>18/13</td>
<td>18/13</td>
<td>18/13</td>
</tr>
<tr>
<td>19</td>
<td>Mask fabrication, device processing</td>
<td></td>
<td></td>
<td></td>
<td>19/16</td>
<td>19/16</td>
<td>19/16</td>
</tr>
<tr>
<td>20</td>
<td>Fabricate and test TIR mirrors</td>
<td></td>
<td></td>
<td></td>
<td>20/13</td>
<td>20/13</td>
<td>20/13</td>
</tr>
<tr>
<td>21</td>
<td>Design and Fabrication Larger Devices with Wavelength Selective Coupling</td>
<td></td>
<td></td>
<td></td>
<td>21/15</td>
<td>21/15</td>
<td>21/15</td>
</tr>
<tr>
<td>22</td>
<td>Fabricate and test TIR mirror with InP waveguide</td>
<td></td>
<td></td>
<td></td>
<td>22/16</td>
<td>22/16</td>
<td>22/16</td>
</tr>
<tr>
<td>23</td>
<td>Design, fabricate and test multiple waveguides and mirrors on single InP chip</td>
<td></td>
<td></td>
<td></td>
<td>23/09</td>
<td>23/09</td>
<td>23/09</td>
</tr>
<tr>
<td>24</td>
<td>Demonstrate InP TIR mirror with waveguide</td>
<td></td>
<td></td>
<td></td>
<td>24/27</td>
<td>24/27</td>
<td>24/27</td>
</tr>
<tr>
<td>26</td>
<td>Directly modulated OEIC-WC</td>
<td></td>
<td></td>
<td></td>
<td>26/13</td>
<td>26/13</td>
<td>26/13</td>
</tr>
<tr>
<td>27</td>
<td>Developing growth and processing technologies to fabricate integrated PICs with tunable lasers</td>
<td></td>
<td></td>
<td></td>
<td>27/16</td>
<td>27/16</td>
<td>27/16</td>
</tr>
<tr>
<td>28</td>
<td>Fabrication and characterization of directly modulated OEIC-WC</td>
<td></td>
<td></td>
<td></td>
<td>28/15</td>
<td>28/15</td>
<td>28/15</td>
</tr>
<tr>
<td>29</td>
<td>Evaluate analog and digital properties of directly modulated devices</td>
<td></td>
<td></td>
<td></td>
<td>29/05</td>
<td>29/05</td>
<td>29/05</td>
</tr>
<tr>
<td>30</td>
<td>Delivery of directly modulated OEIC wavelength converter to DARPA designated government or FFRDC test facility</td>
<td></td>
<td></td>
<td></td>
<td>30/13</td>
<td>30/13</td>
<td>30/13</td>
</tr>
<tr>
<td>31</td>
<td>Design PDEAM with no Interface electronics</td>
<td></td>
<td></td>
<td></td>
<td>31/13</td>
<td>31/13</td>
<td>31/13</td>
</tr>
<tr>
<td>32</td>
<td>Study and assess alternative SOA and detector designs for the directly modulated devices</td>
<td></td>
<td></td>
<td></td>
<td>32/13</td>
<td>32/13</td>
<td>32/13</td>
</tr>
<tr>
<td>33</td>
<td>Study and evaluate survivability and mission lifetimes of directly modulated devices</td>
<td></td>
<td></td>
<td></td>
<td>33/13</td>
<td>33/13</td>
<td>33/13</td>
</tr>
<tr>
<td>34</td>
<td>Design and simulate various embodiments of PDEAM modulated wavelength converters</td>
<td></td>
<td></td>
<td></td>
<td>34/13</td>
<td>34/13</td>
<td>34/13</td>
</tr>
<tr>
<td>35</td>
<td>Report on design considerations for PDEAM devices with no interfaces</td>
<td></td>
<td></td>
<td></td>
<td>35/13</td>
<td>35/13</td>
<td>35/13</td>
</tr>
</tbody>
</table>
6. Appendix B: Budget Summary for FY02-FY03

The target, expended, expended and committed and balance amounts are shown as of end of August 2003 below.