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Waveguide Modulator for Interference Tolerant Functional Near Infrared Spectrometer (fNIRS)

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Abstract

Many crew-related errors in aviation and astronautics are caused by hazardous cognitive states including overstress, disengagement, high fatigue and ineffective crew coordination. Safety can be improved by monitoring and predicting these cognitive states in a nonintrusive manner and designing mitigation strategies. Measuring hemoglobin concentration changes in the brain with functional Near Infrared Spectroscopy (fNIRS) is a promising technique for monitoring cognitive state and optimizing human performance during both space and aviation operations. A compact, wearable fNIRS system would provide an innovative early warning system during long duration missions to detect and prevent vigilance decrements in pilots and astronauts. This effort focused on developing a waveguide modulator for use in an fNIRS system.

Introduction

Many crew-related errors in aviation and astronautics are caused by hazardous cognitive states including overstress, disengagement, high fatigue and ineffective crew coordination. Safety can be improved by monitoring and predicting these cognitive states in a nonintrusive manner and designing mitigation strategies. Measuring hemoglobin concentration changes in the brain with functional Near Infrared Spectroscopy (fNIRS) is a promising technique for monitoring cognitive state and optimizing human performance during both space and aviation operations. A compact, wearable fNIRS system would provide an innovative early warning system during long duration missions to detect and prevent vigilance decrements in pilots and astronauts.

fNIRS is implemented by photon scattering an input coherent source which travels through brain tissue, modifying the intensity and phase of the signal according to the change of oxygen level in the hemoglobin. Current cognitive studies of the human brain use the commercially available Imagent™ (ISS, Inc.) system in a laboratory environment which implements continuous-wave (CW) fNIRS, directly modulating a semiconductor laser at 110 MHz and detecting with a sensitive photomultiplier tube. This modulation frequency is highly susceptible to radio frequency interference (RFI) and the technique is sensitive to slight movements of the headgear. Modulation depth is only 25 percent or less, and signal to

noise ratio is very low. Detection of a usable signal when using the Imagent™ is often very difficult and the system is also extremely bulky at ~70 lb in two 10- by 17- by 18-in. boxes. A new approach is clearly needed if fNIRS is to be used to detect cognitive state in the field.

In fiscal year (FY) 17 the Crew State Monitor (CSM) team built an innovative Frequency Domain (FD) fNIRS system (slated for human flight simulator testing in FY18) which improves upon the commercial design by:

1. Use of FD fNIRS which allows for measurement of absolute oxygenated and deoxygenated hemoglobin concentrations even if the headgear probe were moved due to vibration, g-levels or other environmental conditions.
2. External modulation of the laser instead of directly modulating the laser injection current, achieving close to 100 percent modulation depth, significantly improving the <25 percent modulation depth achieved by the Imagent™.
3. Modulation at 40 MHz instead of 110 MHz, separating the signal of interest from the ambient RFI and improving signal to noise since the noise is an integral multiple of 110 MHz.

This fNIRS system uses a bulk modulator because of its higher efficiency, ability to accommodate multiple wavelengths, and optical throughput, but it requires tedious and time-consuming optical alignment which needs to be precisely maintained during use. Implementation of the modulator in waveguide, which is small, light, and needs no alignment, is essential to miniaturization of the fNIRS system into a wearable device suitable for space and aeronautics applications. This effort focused on the development of the waveguide modulator, which is a parallel effort to the deliverable fNIRS FY17 hardware. Once developed, the waveguide modulator can be used to replace the bulk modulator in the current design, achieving the next step to a compact, wearable unit for measurement of cognitive state in the field. Figure 1 is a block diagram of how the waveguide modulator can be integrated into the current test hardware.

An active test phantom was also developed during the effort which is the first to include circulating fluid with particles that simulate vascular hemoglobin. Since a true frequency domain fNIRS calibration standard does not exist, this test phantom will provide the ability in future testing to precisely calibrate the FD fNIRS instrument to a known standard. The active phantom is shown in Figure 2.

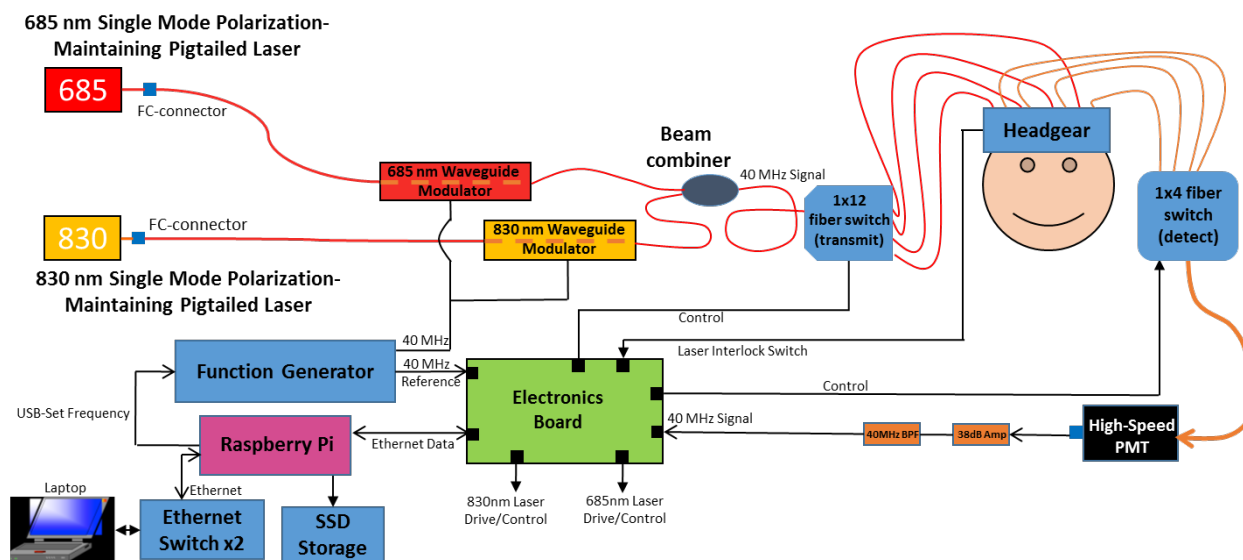


Figure 1.—fNIRS Device System Diagram.

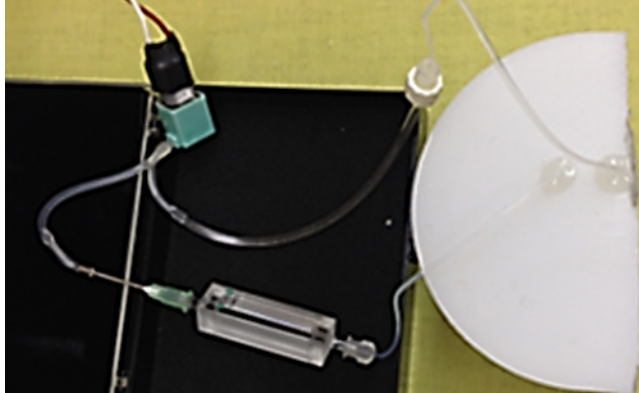


Figure 2.—CIF-developed Active Test Phantom.

Results

During initial testing of the waveguide modulator, four configurations were tested, two in a matched laser to modulator configuration, and two in a mismatched configuration. The configurations were:

1. 685 nm laser into a 635 nm modulator
2. 830 nm laser into an 830 nm modulator
3. 685 nm laser into a 830 nm modulator
4. 830 nm laser into a 635 nm modulator

A Waveguide Modulation Test was run for all configurations (only matched Configurations 1 and 2 shown in Figure 3), all components were directly connected, 14 mW polarization maintaining (PM) fiber-coupled 685 and 830 nm lasers and a Hamamatsu H10721-20 photomultiplier tube (PMT) were used which match the components used in the current fNIRS deliverable system. The 685 nm laser was matched to a 635 nm waveguide modulator which is a standard product. A matched 685 nm custom modulator was later procured but did not arrive in time for testing. Luckily, adequate signal was achieved using the 635 modulator with the 685 laser. Configurations 1 to 3 all performed well, the modulated 40 MHz signal was strongly received at the PMT. Running the 830 nm laser into the 635 nm modulator did not have a usable signal detected, the 830 nm light was too far outside of the 635 nm modulator narrow spectral bandwidth. Testing continued with Configurations 1 to 3 to the Functionality Test (Figure 4).

For the Functionality Test, the modulator and the PMT were no longer directly connected, the modulator and H10721-20 PMT were coupled to fibers attached to a collimated lens. The lenses were aligned in free-space and modulation was again tested. Laser input current and received signal amplification/filtering were adjusted to achieve optimal waveforms. A 65 percent modulation depth was received for all three configurations, which is a significantly improvement from the <25 percent modulation depth attained by the commercial Imagent™ system. Signals received were slightly below the levels received during the Modulation Test, but well within detection levels needed by the fNIRS electronics.

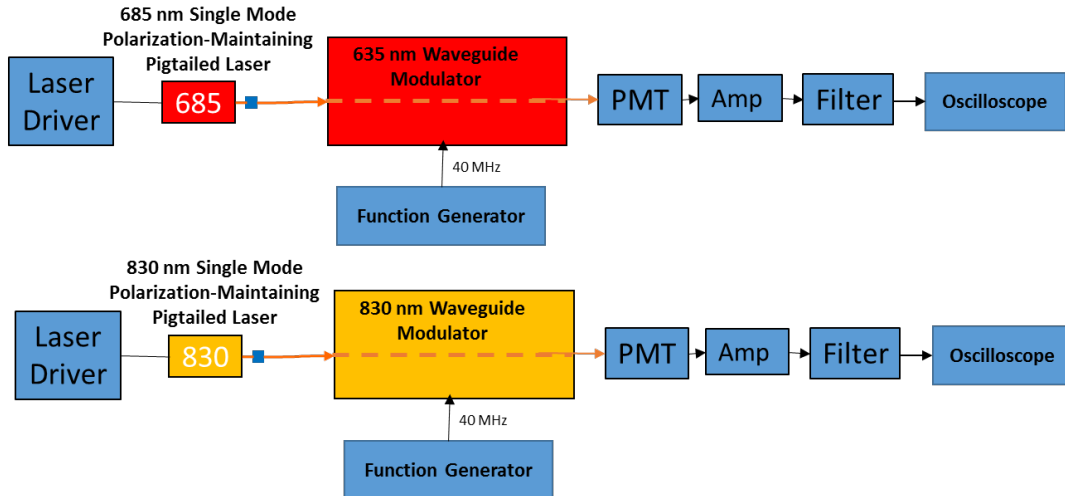


Figure 3.—Waveguide Modulation Test.

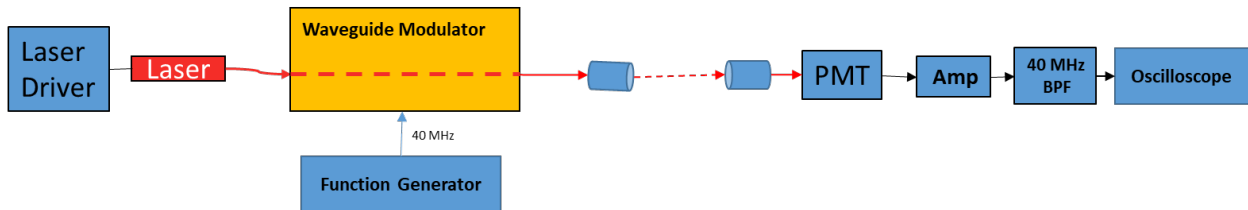


Figure 4.—Functionality Test.

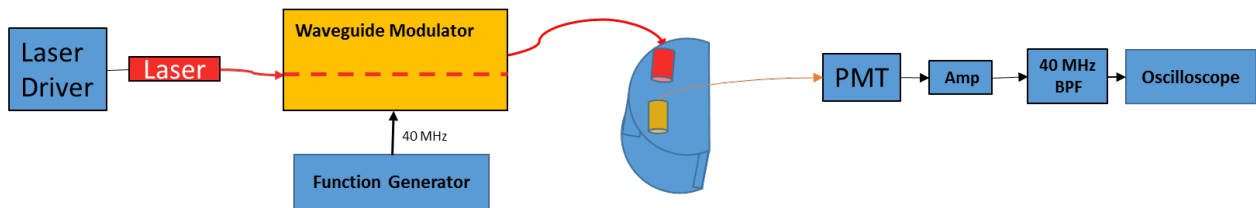


Figure 5.—Active Phantom Test

The mismatched configurations (3 and 4) were attempted to investigate if it might be possible to run both lasers through the same modulator, which would eliminate one costly modulator (~\$7k), greatly reducing the cost, complexity, and size of the fNIRS system. It was found that acceptable signal could be attained by running both lasers through a single 830 nm modulator (but not the 635 nm). Further testing would be needed to verify that this configuration would work when included in the entire fNIRS system, but it was a promising result which could lead to a great refinement of the fNIRS design. This idea has been left as future work, testing continued onto the Active Phantom Test (Figure 5) using only the matched configurations (1 and 2).

For the Active Phantom Test the modulators and H10721-20 PMT were coupled to fibers attached to a collimated lens, and both lenses were inserted into the phantom as shown in Figure 6, and diagrammed in Figure 5.

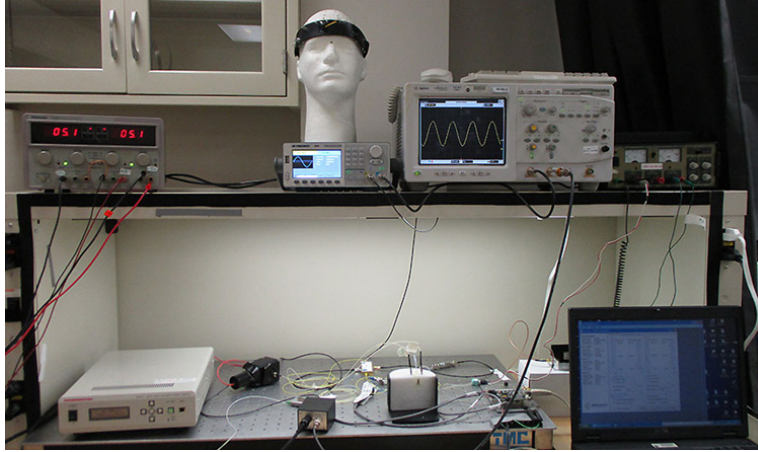


Figure 6.—Final test configuration of the fNIRS waveguide modulator.

Both 685 and 830 nm matched configurations were tested with the active phantom. Unfortunately, neither configuration lead to an acceptable received signal. Variations of laser input current and received signal amplification/filtering were attempted without success. The 90 percent loss of the waveguide modulator resulted in only 255 μW max at the output of the transmit lens, which, after scattering in the phantom, resulted in not enough light input to the H10721-20 PMT to be detected.

Two options were considered:

1. Procure a more powerful laser—The fNIRS application requires a laser coupled to PM fiber, after exhaustive search no higher power PM fiber-coupled lasers were found at the necessary wavelengths. This approach would also be limited to the 30 mW input limit of the modulators, which result in a 3 mW max output after the 90 percent loss. This is extremely low considering that safe skin exposure level is ~ 19 mW at the fNIRS wavelength of 685 nm (35 mW at 830 nm).
2. Procure a more sensitive/higher gain PMT, which may be able to detect this small signal, with the risk that the increased gain will amplify noise as well as the signal of interest.

Since option 1 was not possible, it was decided to procure a better PMT. A Hamamatsu R12829 PMT was ordered which has approximately the same sensitivity as the original PMT but 10 times the gain.

Testing continued with the R12829 PMT and the 830 nm laser. By the time the new PMT was delivered the 685 nm laser had stopped working and no spares were available. R12829 sensitivity at 830 nm is slightly less than at 685 nm, making our test the worst case.

A Functionality Test was run and acceptable output was obtained from the PMT. The Active Phantom Test was then rerun. Variations of laser input current and received signal amplification/filtering were attempted without success, an acceptable signal could not be obtained under any combination of parameters. The additional gain of the R12829 PMT was not enough to detect the very small amount of signal received, and only amplified noise was displayed.

Conclusions and Next Steps

At the initiation of this project it was stated that a key challenge of this work was overcoming the 90 percent loss of the commercial waveguide modulators. During the performance period we have built the waveguide modulator, tested it using the active phantom also built during this effort, and varied key parameters such as laser input current, filtering and amplification stages, and PMT gain. Despite

exhaustive search no higher power PM fiber-coupled lasers are available at the fNIRS wavelengths and no alternate source for the waveguide modulators can be found.

The second key challenge identified was maintaining signal to noise ratio, modulation depth, and phase noise in a LAN Mobile interference environment. All testing was done in a room with known high interference levels due to a LAN Mobile antenna located on the roof, and all tests were performed on a lab bench without any shielding enclosures, a worst-case condition for testing the effects of EMI. Clean signals were obtained during the Modulation and Functionality Tests, amplification and filtering eliminated almost all of the interference. Even though we were not able to detect a usable signal during the Active Phantom Test due to the extremely small amount of light received, it is unlikely the result would be different since the electronics will behave the same for all tests.

A working waveguide modulator is still needed to continue the development of a wearable fNIRS device. At this point the only option left is to modify the commercial waveguide modulators to greatly reduce the 90 percent loss. Research was performed to determine the cause of this large loss, and a modification of the waveguide modulator was proposed which should virtually eliminate this loss. When successfully operational, the low loss waveguide modulator can immediately be used to replace the current bulk modulator in the current fNIRS test device, making a large step towards miniaturization and a significant improvement from commercial offerings.

