High-Definition Raman-based Distributed Temperature Sensing

HDRDTS

Janay Amber Wright Frazier

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Engineering

Anbo Wang, Chair
Yizheng Zhu
Wei Zhou

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Keywords: Stokes, Anti-Stokes, Raman DTS
Distributed Temperature Sensing (DTS) has been used in a variety of different applications. Its ability to detect temperature fluctuations along fiber optic lines that stretch for several kilometers has made it a popular topic in various fields of science, engineering, and technology. From pre-fire detection to ecological monitoring, DTS has taken a vital role in scientific research. DTS uses the principle of backscattering by three different spectral components, e.g., Rayleigh scattering, Brillouin scattering, and Raman scattering. Although there have been various improvements to DTS, its slow response time and poor spatial resolution have been hard to overcome. Its repetition rate is low because the pulse must travel the distance of the fiber optic line and return to the detector to record the temperature change along the fiber. A spatial resolution of 7.4 cm with a response time as low as 1 second and a temperature resolution of the 0.196 °C is achieved from the current DTS system. This research proves that high-spatial resolution can be obtained with the use of a Silicon Avalanche Photodetector with a 1 GHz bandwidth.
Sensors have been used for a variety of purposes such as to measure temperature and strain. Recent literature suggests that distributed temperature sensing (DTS) is a unique approach to measure temperature. DTS allows continuous, real-time measurements along a fiber optic cable. My research focused on improving the DTS system. A high-resolution Raman-based DTS was developed by 1) enhancing its spatial resolution, 2) shortening response time, 3) improving temperature resolution, and 4) extending the sensing distance. By enhancing these parameters, it will provide a wide range of new possibilities to the field of optical fiber sensing.
ACKNOWLEDGMENTS

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I would also like to acknowledge my colleagues at the Center for Photonics Technology (CPT) for helping me work through this perplexing task.

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“I can do all things through Christ who strengthens me.”

— Philippians 4:13
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1 Introduction

1.1 Overview

Distributed Temperature Sensing (DTS) was first introduced in the 1980s and has made a major contribution to the field of fiber-optic sensing [1]. Its ability to measure temperature along a fiber optic line has served as a way to monitor gas pipeline integrity [2]. Since then, DTS has been modified in order to, for example, monitor structural health of bridges and other structures that are reinforced by concrete beams [3], [4]; detect leakages for not only gas and oil pipelines [5] but dams and dikes to prevent flooding [6]; and to detect fires [7]. With the ever-growing safety hazards within the world, development of new technological enablers is needed to ensure the safety. For instance, DTS has been a technological enabler in environmental science monitoring providing high spatial resolution for hydrologic process monitoring [8] and Traction Transformer Monitoring. So far, an accuracy of ±1 °C at a resolution of 0.01 °C with a spatial resolution of 1 m over a DTS distance of 30 km has been reported [3]. Thus, the implementation of DTS within these hard-to-work areas would improve the quality of life for people with high hazard jobs.

1.2 DTS Scattering

Scattering is an inherent property of a material [9]. Scattering is when energy waves interact with a material causing the waves to deviate from its original path. The scattering of light waves, sound waves or other moving particles are broken down into elastic and inelastic scattering [9]. Elastic scattering is when the frequency of a particle remains unshifted through the scattering event, however, the particle deviates from its initial direction [9]. A major form of elastic (coherent) scattering is Rayleigh scattering [10]. A well-known example of this type of scattering is the interaction between light and matter causing the sky to be blue during the daytime [9]. Inelastic
scattering is when the energy of a particle is not the same as its initial frequency after it is scattered [9]. Examples of inelastic (incoherent) scattering are Brillouin and Raman scattering [9, 10]. One of the major applications that utilize scattering as a primary principle of detection is Distributed Temperature Sensing (DTS) [3]. DTS is when a light pulse is launched into a fiber that is put in place to detect a strain and temperature change along the fiber optic line. When the change occurs there are three different spectral components of the back-scattering signal that takes place: Rayleigh scattering, Brillouin scattering, and Raman scattering as shown in Figure 1.

Figure 1 Return signal intensity as a function of wavelength in DTS

The spatial resolution of a DTS sensor is the minimum distance for change to be detected in the backscattered signal [11]. Since DTS uses Optical Time Domain Reflectometry (OTDR) for localization shown in Figure 2 [6], to detect the backscattered signal, the signal in the time domain can be converted to the spatial domain. Equation 1 shows the conversion from the time domain to the space domain:

$$\Delta L = \frac{tc}{2n}$$ (1)
where $n$ is the index of refraction of the fiber material at the wavelength of the pulsed laser, $c$ is the speed of light, and $L_2$ is the two-way path that the light must travel. Figure 2 is a depiction of an OTDR DTS system that a) sends a pulsed laser light down b) a multimode optical fiber and c) the beam splitter couples light into d) a spectrometer that captures e) the forward traveling incident light that is f) back-scattered.

![Figure 2 Depiction of OTDR DTS system to measure temperature along a fiber [12]](image)

1.3 Rayleigh and Brillouin Scattering DTS

For the Rayleigh phenomenon and its interaction to a fiber material, its wavelength remains unshifted and is the same as the light source center wavelength. Rayleigh scattering has the highest intensity of the three spectral components of scattering and it is sensitive to both strain and temperature. The refractive index perturbation causes the Rayleigh component to be back-scattered as shown in Figure 3. Although this form of scattering is sensitive to temperature changes, it does not preferable for this application because it requires large amounts of tuning and calibration.
Besides Rayleigh scattering, Brillouin scattering is one example of the interaction between single-wavelength light waves and sound waves; it is also sensitive to both temperature and strain. This is a type of scattering that stems from lattice vibrations of a material and its collision is inelastic. The Brillouin scattering includes two bands known as Stokes and Anti-Stokes bands [13]. However, like Rayleigh-based DTS, Brillouin based DTS requires a lot of signal demodulation making it difficult to tune.

1.4 Raman-based DTS

The third spectral component is known as Raman backscattering which is sensitive to temperature alone. These oscillations have a positive shifted frequency known as Anti-Stokes $+\Delta \nu$ and a negatively shifted frequency $-\Delta \nu$ Stokes as shown in Figure 1. For DTS applications, Raman based DTS systems are the most often used because Rayleigh and Brillouin scattering are used to simultaneously measure temperature and strain, which requires very careful calibration [14], [15], [16]. However, Raman based DTS sensing has a very small strain crosssensitivity. Calculating its temperature response is far less complicated than the previous two methods. By taking a ratio of intensities of the Anti-Stokes signal $A_{as}$ and the Stokes signal $A_{s}$, gives the temperature profile, and the location of that temperature change is given by the time stamp of the change. At a certain
position along the fiber optic line $L$ in meters, as shown in Equation 1, the intensity of the Stokes and Anti-Stokes signals converts into a temperature measurement as a ratio:

$$T\Delta = \frac{A_{as}}{A_s} = \frac{K_{as}}{K_s} \exp\left(-\frac{h\Delta \nu}{kT}\right)$$

(2)

where $K_{as}$ and $K_s$ denote the temperature sensitivity of the Anti-Stokes and Stokes signals at room temperature, respectively, $T$ denotes the specific temperature step that is being measured, $h$ is the Planck constant and $k$ is the Boltzmann constant [17]. This relationship of amplitudes, as it pertains to the number of photons, is also depicted in Figure 4. Therefore, Raman based DTS is the most reliable mechanism for measuring temperature along an optical line because the signal can easily be demodulated and most importantly it allows for ultra-fast real-time acquisition of the signal. Other important parameters for DTS include response time, which is the amount of time it takes for the signal to be acquired from the sensor and maximum sensing distance.

*Figure 4 Relationship between a number of photons in Anti-Stokes and Stokes bands. [12]*
1.5 Construction of Raman-based DTS

Based on the literature most Raman-based DTS systems are comprised on a few essential components: a pulse laser (light source), a fiber optic cable, a Wavelength-Division Multiplexer so that Stokes and Anti-Stokes bands can be separated, then captured by a detector [18]. Historically, Raman-based DTS systems research has explored different types of detectors that capture the Stokes and Anti-Stokes signals to improve the signal response. The detectors used to measure the backscattered light of the Stokes and Anti-Stokes signals are in order from lower to higher response: Avalanche Photodiode Detector (APD) [1], [18], Photomultiplier Tube Detector (PMT) [1], [19], or Single-Photon Avalanche Detector (SPAD) [19], [20].

With those different methods of improving the response time and signal strength of the measurements, there have also been three types of main calibration methods used in DTS systems. These calibration methods that presented in the literature are; single-ended, duplexed single-ended and double-ended [21], and their fiber configurations are shown in Figure 5. Single-ended DTS calibration involves only a single end of the fiber optic line to be connected to the measuring instrument. While duplexed single-ended calibration involves the fiber optic line to be placed parallel to the original line that is heated. Lastly, double-end the fiber beginning and its end to be connected to the DTS measuring instrument [22].
1.6 Applications of DTS in Industry

Companies such as Schlumberger®, Omnisens®, and SensorTran® have manufactured various DTS systems that have been integrated into many of their industrial partners’ network. Table 1 shows a summary of their products and what application purposes they fulfill.

<table>
<thead>
<tr>
<th>Manufactures</th>
<th>Products</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schlumberger®</td>
<td>WellWatcher Neon DTS</td>
<td>Gas well flow analysis</td>
</tr>
<tr>
<td></td>
<td>DAS PT</td>
<td>Water injection monitoring</td>
</tr>
<tr>
<td></td>
<td>Gauge System® [23]</td>
<td>Well integrity monitoring</td>
</tr>
<tr>
<td>Omnisens®</td>
<td>DITEST-®</td>
<td>Strain</td>
</tr>
<tr>
<td></td>
<td>LYNX® COBRA®</td>
<td>Fatigue</td>
</tr>
<tr>
<td></td>
<td>SUBSEA® [24]</td>
<td>Temperature</td>
</tr>
<tr>
<td>SensorTran®</td>
<td>ASTRA®</td>
<td>DTS product families</td>
</tr>
<tr>
<td></td>
<td>GEMINI®</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NEPTUNE® [25]</td>
<td></td>
</tr>
</tbody>
</table>
Pressure-temperature gauge (i.e. a combination of products from Schlumberger®) is a combination of three optical fibers to provide a single downhole cable that is able to be used simultaneously to monitor temperature, acoustic data, pressure changes [23]. This type of technology is ideal for real-time data acquisition to monitor reservoirs, gas flow, and in a wellbore or near-wellbore areas [23].

![Figure 6 Omnisens-Lynx DTS system a) in the ground, and b) as a cross-section; c) characteristic indications due to pipeline integrity changes [24]](image)

Much like Schlumberger®, Omnisens® developed their LYNX® product operate as a continuous DTS system that monitors gas and oil pipeline integrity in real time, as shown in Figure 6a. As shown in Figure 6b, the LYNX® system used the placement of an optical sensing fiber cable
outside of the pipeline to detect leaks, ground movement, and third party intrusion. Figure 6c is the characteristic indicators to which type of change is occurring. For example, an indication of a gas leak will be a sudden decrease in temperature below zero due to cooling effect [24], [26], oil is normally warmer than ambient soil there will be an increase in temperature when there is an oil leak [24], and for erosion or soil movement can be detected as an increase or decrease in temperature depending on the season in which the change occurs [24].

Lastly, SensorTran® utilizes DTS in their product Gemini [27]. Gemini is a hydrogen tolerant tool that is used in harsh environments to survey the fiber optic line used in geothermal applications [27]. This product has been able to measure a range up to 5 km with a spatial resolution of 1 meter, a temperature resolution of 0.1 ºC and an update interval as fast as 10 seconds [25].
2 Motivation

2.1 Raman-based DTS in Literature

Summarized from the previous Section, four parameters that make a high definition DTS sensor are as follows: a reduced spatial resolution, a fast response time, an increased temperature resolution, with an extended sensing distance. Although DTS has been an enabler in many different areas as mentioned previously, it has many drawbacks that have dampened its commercial use such as poor repetition rate, limited sensing distance with accuracy, the limited threshold of smallest resolvable temperature resolution and poor spatial resolution. Many researchers have improved these parameters as summarized in Table 2. Dr. Bo Liu, improved the spatial resolution of his sapphire-fiber based Raman DTS sensor to the 10 cm level with a repetition rate as low as 0.1 s using a passively Q-switched microchip laser and APD’s to capture the Raman signal; however, he was only able to achieve a temperature resolution on the 3 °C level [18]. Researchers such as Richardo Feced [19] and D.A. Thomcraft [20] also achieved a spatial resolution as low as the 0.1 m level, however, they implemented photomultiplier tubes, which enhanced the photon counting in a weak signal such the Raman Stokes and Anti-Sokes intensities. Lastly, while Authors Y. Chen [28] and M.A. Soto [29] were not able to achieve a very reduced spatial resolution like the previous researchers; they forfeited reducing the spatial resolution to improve maximum sensing distance to >1 km and 26 km respectively.
Table 2 Summary of literature on Raman-based DTS

<table>
<thead>
<tr>
<th>Reference</th>
<th>Laser Description</th>
<th>Sensor Type</th>
<th>Fiber Type</th>
<th>Sensing Distance</th>
<th>Rep Rate</th>
<th>Spatial Resolution</th>
<th>Temperature Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liu, B., 2016 [18]</td>
<td>Q-switched 532 nm</td>
<td>APD</td>
<td>GRIN and Sapphire MM</td>
<td>3 m</td>
<td>0.1 s</td>
<td>0.1 m</td>
<td>3 °C</td>
</tr>
<tr>
<td>Chen, Y., 2014 [28]</td>
<td>1064 nm</td>
<td>APD and transimpedance preamplifier</td>
<td>50/125 MM</td>
<td>&gt; 1 km</td>
<td>1 s</td>
<td>0.4 m</td>
<td>0.56 °C</td>
</tr>
<tr>
<td>Soto, M. A., 2011 [29]</td>
<td>1550</td>
<td>-</td>
<td>SM</td>
<td>26 km</td>
<td>30 s</td>
<td>1 m</td>
<td>3 °C</td>
</tr>
<tr>
<td>Feced, R., 1997 [19]</td>
<td>Gain-switched Pulsed semiconductor laser 635 nm</td>
<td>Photomultiplier</td>
<td>GRIN MM</td>
<td>20 m</td>
<td>60 s</td>
<td>0.1 m</td>
<td>2–4 °C</td>
</tr>
<tr>
<td>Thomcraft, D. A., 1992 [20]</td>
<td>Mode-locked Nd-YAG</td>
<td>Photomultiplier</td>
<td>SM</td>
<td>-</td>
<td>360 s</td>
<td>0.1 m</td>
<td>5 °C</td>
</tr>
</tbody>
</table>
The motivation of this work is to increase the spatial resolution by pushing the laser pulse repetition frequency to its limit, which increases the repetition rate of the sensor. By doing so, this will increase the accuracy of small area detection for distributed temperature sensing. Therefore, we wanted to push the limit of spatial resolution which is ultimately as good as our hardware. A challenge for DTS has been finding the right procedures that will increase the sensitivity and spatial resolution along the fiber optic line [19].

2.2 Specific Aims

Raman DTS spatial resolution of a less than 10 cm was reported with the limiting factor of a 1 GHz APD. The temperature resolution, Stokes and Anti-Stokes intensity, and frequency of the RDTS detection system were evaluated. This type of capability will be suitable for high-speed sensing in various fields. The four aims of this thesis were to:

1) Decrease the slow response time to the 0.1 s level;
2) Reduce poor spatial resolution $< 0.1$ m;
3) Increase the temperature resolution down to the 0.01 °C level; and
4) Extend the sensing distance beyond 20 m.
5) By heating a small section of the fiber we can then verify a high spatial resolution.
3 Approach

3.1 Spatial Resolution

To achieve a spatial resolution less than $\Delta L = 10 \, cm$, the size of the time $\Delta t$ window to capture the backscattered window must be the following [11]:

$$\Delta t = \frac{2 \ln \frac{2 \times 1 \, m \times (1.4607)}{c}}{c} = 9.738 \times 10^{-10} \, s = 0.97 \, ns \quad (3)$$

The spatial resolution can be determined by taking the 10%-90% levels of the temperature response time [11], [28]. As shown in Figure 7, the levels are determined by evaluating 100% level which defines the temperature step then, taking away 10% of that 100% level to locate the 90% level. From there, the 10% level can be determined the same way by evaluating the 0% level. For the spatial resolution, a ratio for Stokes to Anti-Stokes is taken by the previous equation 2 located in Section 1.4.

![Figure 7 Spatial resolution for a Raman-based DTS system as defined by 10-90% principle](image-url)

### 3.2 Spatial Resolution Analysis and Limitations

The pulse width of the laser and the sampling interval are key components in analyzing the ultimate temperature distribution along the fiber when determining the spatial resolution of the Raman-based DTS system. To improve on the functionality of a DTS system, there are parameters that must be assessed such as temperature resolution, spatial resolution, and minimum measurement length, which are all determined by multiple factors including components of the laser pulse and sampling interval. The distance covered by the 700 ps laser light pulse is:

\[
v = \frac{c}{n} = \frac{3 \times 10^8 \text{m/s}}{1.4607} = 2.054 \times 10^8 \text{m/s} \tag{4}\]

To achieve the minimum 10 cm spatial resolution, the time window required is calculated as follows:

\[
\Delta t = \frac{2\Delta L}{v} = \frac{2 \times .10 \text{ m}}{2.054 \times 10^8} = 974 \text{ ps} \tag{5}\]

The minimum time between launches is also a very important factor to consider. Considering that the fiber optical line is 100 m line and \(n = 1.4607\):

\[
Time \text{ between launches} = \frac{2 \times 100 \text{ m}}{v} = 9.717 \times 10^{-7} \text{ s} \tag{6}\]
3.3 Modal Dispersion

Since the fiber is multimode, we must take modal dispersion into account because different modes propagate with different group delay, which is known as model dispersion [30]. Since a multimode silica graded index fiber is utilized for the sensing cable line, the delay of the modes for a graded index fiber are as follows [18]:

\[
\Delta t = \frac{nL\Delta^2}{2c} \quad (7)
\]

where \( n \) is the refractive index of silica fiber core which hailed at 1.4607, the length of the fiber, \( L \), in meters, the speed of light in vacuum, \( c \),

\[
\Delta = \frac{NA^2}{2n^2} \quad (8)
\]

where the numerical aperture denoted by N/A, or Not Applicable. If we assume that \( \Delta \ll 1 \), the spatial resolution is

\[
SR = (\Delta t + t)\frac{c}{2n} \quad (9)
\]

where \( t \) is the time duration of the pulse which is 700 ps. The ultimate spatial resolution of the DTS system was evaluated at different lengths by the previous Equations 8-10. In Figure 8, the length of the fiber was evaluated at 2, 10, 20, and 100 meters showing the linear relationship of
spatial resolution to the length of the fiber as the length of the fiber increases the spatial resolution also increase due to modal dispersion.

Figure 8 Estimated maximum spatial resolution for a) 2-meter fiber, b) 10-meter fiber, c) 20-meter fiber, and d) 100 meter fiber
4 Experimental Set-up and Protocol

4.1 Module Overview

The DTS system shown in Figure 9, monitored temperatures from room to 124 °C silica fiber from lengths 2 m to 100 m. A Q-switched laser (Concepts Research Corporation, SPL Laser) with source functioning at a wavelength of 532 nm launches a pulse as short as 700 ps with a pulse energy of 5 µJ making the peak power 7 kW into the fiber. The fiber was a Graded Index (Corning, Infinicor 300), with 62.5 µm core and 125 µm clad was placed through the heated furnace that was 10 cm in length. The configuration of the furnace will be further discussed in Section 4.3. That pulsed laser light starts off by passing through two collimating lenses. Next, the beam is separated by a 50:50 beam splitter. The two paths of the separated beam are directed simultaneously into one-trigger signal monitored by a trigger detector and the other beam is aligned into the silica fiber. During the heating of the furnace, the Raman scattered signal then returns through the 50:50 beam splitter to be monitored by the two APD detectors (Thorlabs, APD210) capturing the signal of the filtered Stokes and Anti-Stokes light. Each acquisition was taken using a LabVIEW code that pulled the data from the high-speed oscilloscope (Lecroy, WavePro Zi-A).

Tables 3 are the components used to filter the DTS signal, Table 4 are sensing components used to detect the signal, and Table 5 are other miscellaneous components used in the DTS system.
Figure 9 Module overview of high definition DTS system

Table 3 Filtering components for the DTS system

<table>
<thead>
<tr>
<th>Filters</th>
<th>Type</th>
<th>Center wavelength</th>
<th>Model Number</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser reject filter</td>
<td>Notch Filter</td>
<td>532 nm</td>
<td>NF01-532U-25</td>
<td>Semrock [31]</td>
</tr>
<tr>
<td>Dichroic beam splitter</td>
<td>Dichroic mirror</td>
<td>535 nm</td>
<td>FF535-SDi01-25x36</td>
<td>Semrock [32]</td>
</tr>
<tr>
<td>Anti-Stokes filter</td>
<td>Band pass</td>
<td>512 nm</td>
<td>FF01-512/25-25</td>
<td>Semrock [33]</td>
</tr>
<tr>
<td>Stokes filter</td>
<td>Band pass</td>
<td>543.5 nm</td>
<td>FF01-550/88-25</td>
<td>Semrock [34]</td>
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</table>

Table 4 Sensing components for signal detection

<table>
<thead>
<tr>
<th>Name</th>
<th>Bandwidth</th>
<th>Model Number</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 APD</td>
<td>1 GHz</td>
<td>APD210</td>
<td>Thorlabs [35]</td>
</tr>
<tr>
<td>OSC</td>
<td>&lt; 2.5 GHz</td>
<td>WavePro 725Zi-A</td>
<td>Lecroy [36]</td>
</tr>
</tbody>
</table>
Table 5 Miscellaneous components used in DTS system

<table>
<thead>
<tr>
<th>Name</th>
<th>Model Number</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Source</td>
<td>SPL Laser, s/n 000123 w/PD</td>
<td>Concepts Research Corporation</td>
</tr>
<tr>
<td>Furnace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current source</td>
<td>PC-3030D</td>
<td>GW Instek [37]</td>
</tr>
<tr>
<td>Thermometer</td>
<td>HH147U</td>
<td>Omega [38]</td>
</tr>
<tr>
<td>Fiber</td>
<td>Infinicor 300</td>
<td>Corning [39]</td>
</tr>
</tbody>
</table>

4.2 Furnace Configuration

To verify the increase in the spatial resolution of the detection, the heating length was decreased from a foot which is around 30.48 cm to 10 cm. First, a hole was drilled into a cement block with a diameter of 1.02 cm. Then a non-insulated wire was wrapped around a glass tube 10 cm in length and 1 cm in diameter. The glass tube was then placed into the hole of the cement block. A current source was then connected to induce heating (Figure 10 and 11). The proper measurement was conducted to ensure enough current was induced to stay at the room temperature to the maximum temperature that the fiber could withstand.

Figure 10 Heating Element Configuration
The following procedures were taken to relate temperature to the current in Amps. First, a model of the heat was calculated by determining the Joule heating:

\[ P = I^2 R_L \ \text{[W]} \quad (10) \]

Joule heating is the heat dissipation when a current passes through a non-zero resistance [40]. The Load resistance \( R_L \) was 4.6 ohms. The approach that was taken was similar to the single-ended OTDR Raman-based DTS system where it has one end of the fiber exposed, and the other end of the fiber is connected to the DTS output. However, there was one heating element as shown in Figure 10. There were a total of eleven temperature steps taken starting with room temperature which depending on the day varied between 23-25 °C. Each temperature was monitored by the temperature gage shown in Figure 11. From those eleven different temperature steps, 500 waveforms were taken, which were then averaged together to ensure there was no drifting.

*Figure 11 Monitored temperature with Omega thermocouple with corresponding current setting*
In Optical Time Domain Reflectometry, the Raman frequency shifts are defined as the inverse length that is directly related to the energy difference between the incident and scattered photons. This numerical value of Raman shift is normally reported in wavenumbers (cm\(^{-1}\)). When converting from the spectral wavelength to the wavenumber the following equation is utilized:

\[
\Delta \omega = \left( \frac{1}{\lambda_0} - \frac{1}{\lambda_1} \right) \text{ (11)}
\]

where \(\lambda_0\) is the excitation wavelength or incident wavelength, \(\lambda_1\) is the Raman spectrum wavelength or scattered wavelength, and \(\Delta \omega\) is the Raman shift. Due to the electrons decaying to different levels makes the type of scattering inelastic, because the Stokes and Anti-Stokes decay to different vibrational states as shown in Figure 12, their equations for Raman shifts are shown in Equations 12 and 13 [18]:

\[
\Delta \omega \ (cm^{-1}) = \left( \frac{1}{\lambda_0 (nm)} - \frac{1}{\lambda_{Stokes} (nm)} \right) \times \left( \frac{10^7 nm}{cm} \right) \text{ (12)}
\]

\[
\Delta \omega \ (cm^{-1}) = \left( \frac{1}{\lambda_{Anti-Stokes} (nm)} - \frac{1}{\lambda_0 (nm)} \right) \times \left( \frac{10^7 nm}{cm} \right) \text{ (13)}
\]
for the Raman spectra of silica fibers its maxima peak shifts is located at 440 cm\(^{-1}\), 490 cm\(^{-1}\), 605 cm\(^{-1}\), 800 cm\(^{-1}\), and 1060 cm\(^{-1}\) [41], [42]. These wavelengths were graphed to solve for Raman shift peaks for both Stokes and Anti-Stokes and are shown in Figures

![Graph of Raman shifts for Stokes and Anti-Stokes signals](image)

*Figure 12 Peaks of Raman shifts for stokes and Anti-Stokes signals*

Due to the distance between Raman peaks of maximum Stokes peaks and minimum Anti-Stokes peaks being at a smaller span at lower wavelengths then higher wavelengths. The use of 532 nm is a viable wavelength be utilized to obtain an increased spatial resolution [18].

![Energy level diagram for Raman scattering](image)

*Figure 13 Energy level diagram for Raman scattering; (a) Stokes and (b) Anti-Stokes Raman scattering [43].*
Table 6 shows the specifications of the Infinicor 300 fiber, which is used in telecommunications. Due to the fact that this laser is operating at 532 nm and the index of the core does not sit at a fixed value, as shown in Figure 14, the GRIN fibers have multiple indices in order to estimate a proper index of refraction the index of silica was used at 532 nm (e.g. n = 1.4607).

![Figure 14 Graded index a) fiber profile and b) light path of the different rays](image)

4.3 Preparation of Graded-Index Fiber

Unlike step-index fiber, graded index fiber is best suited for long-distance sensing due to its graded index profile as shown in Figure 14. The GRIN fiber used in this experiment was a 62.5 /125 μm fiber. To prepare the fiber for experimentation 100 m of the fiber was re-spoled to ensure its length. Then the fiber was polished to ensure maximum coupling to the system. The following is a list of steps taken to re-spool the fiber:

1) An empty spoil is placed on at one end of the spooling machine.
2) The full fiber spool is placed at the other end a seen in Figure 15 at position A.
3) The fiber end of the full fiber is threaded from the spool through a pulley system, then taped to the empty spool.
4) After the spooling machine is turned on the initial value of the controller should be set zero.
5) Then press the on button.
6) The fiber is pulled from position A to position B on Figure 15.
7) Once the counter hits the desired length machine is stopped.
8) Lastly, the two spools are cut from one another.

In the case of the data that was collected the GRIN MM, the fiber was cut at 100 meters.

The following is a list of steps taken to prepare the fiber for polishing:

1) De-coat fiber end with a razor blade.
2) Wipe with isopropyl alcohol to clean.
3) Insert fiber into fiber connector as shown in Figure 16.
4) Epoxy was used to secure fiber into the connector.
5) Set on a hot plate for about an hour.
6) Left overnight to ensure security.

After the fiber was prepared, the fiber was polished using the following steps:

1) To remove the epoxy, the end the fiber was cleaned with sandpaper (Figure 16 and 17).
2) The ferrule of the connector was polished with the polishing machine (Krell, SpecPro™ Connector Polisher [45]) (Figure 18b).

3) The ferrule was polished with 6 µm, 3 µm, 1 µm polishing paper (Figure 18a).

4) The ferrule was cleaned with isopropyl alcohol and inspected with the microscope to replace the polishing papers with the rubber holder (Figure 18a and 18b).

This process was repeated several times in order to reveal a well-polished fiber end (Figure 19).

*Figure 16* fiber connector after Epoxy and before polishing

*Figure 17* Epoxy to bond the fiber into the connector
Figure 18 a) polishing paper b) the Krell, SpecPro $^T$ Connector Polisher[45], complete with the monitor to evaluate fiber end, polisher, microscope, and connector holder

Figure 19 Fiber face after polishing
5 Evaluation and Results

The collected data was retrieved from the oscilloscope using LabVIEW VI and was synthesized into MATLAB. The Stokes and the Anti-Stokes APD detectors were at different length the one another, the difference in time delay was aligned using a Matlab code by selecting the maximum point after removing the noise floor of the signal. Then once aligned, the ratio of Stokes to Anti-Stokes was found and graphed for each temperature to determine the temperature resolution of the Raman-based DTS system. By selecting a maximum point for each temperature Gaussian-shaped curve, temperature resolution was calculated by evaluation of the error bars. In preparation to use the LabVIEW code, the desired average times were set on the oscilloscope. The laser was turned on by setting the following parameters shown in Table 7. The time window, amplitude, offset, and other parameters with the oscilloscope interface were set. The LabVIEW VI in Figure 20 saves a series of waveform sets, the Stokes and Anti-Stokes signals, of different channels simultaneously. The LabVIEW program executes the following:

1) Initializes the oscilloscope and calculates the wait time for each set to get all averaged waveforms, adjusting the value of wait time if more or less time is needed.

2) Starts the waveform acquisition, which is a loop where the program:
   a. Tells the oscilloscope to repeatedly gather waveform;
   b. Waits for averaging;
   c. Stops waveform;
   d. Reads waveform from the oscilloscope to the computer to display; and
   e. Saves each averaged waveform for all waveforms needed to .lvm file.
Figure 20 LabVIEW VI Interface

Table 7 Laser Settings

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<th></th>
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<th>3.16 A</th>
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<td>0.313 A</td>
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<td>TEC1 Set Point</td>
<td>28.9 °C</td>
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<td>TEC2 Set Point</td>
<td>31.04 °C</td>
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<tr>
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<td>Pulse Width</td>
<td>80.1 μm</td>
</tr>
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</table>

5.1 Spatial Resolution Results

Stokes and Anti-Stokes graphs where evaluated from the heated section of the fiber. The baseline of the first 10 frames was taken to get rid of some of the zero measurements. Then files were averaged by the number of waveforms (n = 500) saved at each temperature set. In Figure 21, the Stokes graph was created by using the intensity over time data acquired from the Stokes signal detector. The time data was then converted to distance by Equation 5 solving for ΔL. The same
was done for Figure 22 for the Anti-Stokes signals. Each temperature was graphed by intensity over distance using the MATLAB code located in the Appendix Section 8.2 and Section 8.3.

![Figure 21](image1.png)

*Figure 21* Stokes amplitude in Graded-Index Fiber at 100 m

![Figure 22](image2.png)

*Figure 22* Anti-Stokes amplitude in Graded-Index Fiber at 100 m
Although, there is no noticeable fluctuation in the Stokes and Anti-Stokes amplitudes at the 34.6° and 44.5° measurement, and there was a significant drop. This drop can be due to laser degradation over time as well as a photodetector. However, the drop is well compensated by the $A_{as}/A_s$ ratio as shown in Figure 23.

The spatial resolution was resolved by the 10-90% method for the mean of the eleven temperatures. The spatial resolution for the intensity of the Raman Ratio over distance was 7.04 cm, which is above the minimum threshold of the spatial resolution estimation in Figure 18. Each temperature step is averaged over the 500 acquisitions. The Fiber Distance vs. Ratio Intensity was analyzed by finding the median of the data set then finding the 90% point from finding the maximum of 100% point and finding the 0% point and locating the 10% point. This code is located in Appendix Section 8.1.

![Figure 23 Raman-ratio vs fiber distance on a 100 m fiber](image)
5.2 Temperature Resolution Results

To find the temperature resolution, the standard deviation was found for the Raman ratios at each temperature step, and the results are shown in Table 9 and in Figure 24. The temperature resolution was found as the range found across the standard deviations of the temperatures and was calculated to be at 0.196 °C.

Table 8 Standard deviations of the Raman-ratio at each temperature step

<table>
<thead>
<tr>
<th>Standard Deviation (°C)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
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<tr>
<td>0.208</td>
<td>24.6</td>
</tr>
<tr>
<td>0.211</td>
<td>34.6</td>
</tr>
<tr>
<td>0.197</td>
<td>44.5</td>
</tr>
<tr>
<td>0.208</td>
<td>54.1</td>
</tr>
<tr>
<td>0.198</td>
<td>64.4</td>
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<tr>
<td>0.393</td>
<td>74.5</td>
</tr>
<tr>
<td>0.214</td>
<td>84.1</td>
</tr>
<tr>
<td>0.208</td>
<td>94.4</td>
</tr>
<tr>
<td>0.202</td>
<td>104.5</td>
</tr>
<tr>
<td>0.197</td>
<td>114.6</td>
</tr>
<tr>
<td>0.204</td>
<td>124.7</td>
</tr>
</tbody>
</table>

Figure 24 Temperature vs. Ratio
5.3 Sensing Distance Results

The system was connected to 100 m, and the laser pulse was propagating to the end of the fiber as seen in Figure 25. However, the return Raman signal was recorded up to a little less than 5 m sensing distance as shown in Figure 25. This attenuation within the signal can be attributed to a major nonlinear effect known as the Kerr Effect.

![Figure 25 Propagation of light through the system](image)

5.3.1 Kerr Effect

Kerr Effect is when high pulse laser light that is propagating down an optical fiber causing a modification to the fibers refractive index. This a nonlinear effect that occurs to a high-laser pulse
injection into the fiber causing the light to broaden as it propagates through the fiber [46]. The refractive index is modified by:

\[ \Delta n = n_2 I \]

where \( n_2 \) is the nonlinear index and \( I \) is the light. Silica fibers have a nonlinear index of \( \approx 3 \times 10^{-16} \text{ cm}^2/\text{W} \) [46]. An experiment was conducted to reduce the intensity of light by inserting attenuation filters to reduce the intensity to reduce the index change, \( \Delta n \). As the power injection to the fiber was attenuated by absorptive filters, the sensing range was extended due to the nonlinear index being reduced. Due to the short laser pulse this, simple relationship can be observed called self-steeping [47]. Which is when the group velocity reduces causing an increase in slope of the trailing part of the pulse as seen in Figure 26.

![Figure 26](image.png)

*Figure 26 Evolution of amplitude intensity shift as a function of time*
6 Summary and Future Work

For a sensing distance of 5 m, a spatial resolution of < 0.1 m was obtained for a temperature resolution of 0.3 °C level. Specifically, a spatial resolution of 7.4 cm is far beyond the previous boundary of a 10 cm spatial resolution seen in literature. Other areas of DTS applications may be explored on the centimeter level to detect small temperature changes along a fiber optic line. In addition, by creating a portable module the high-definition Raman-based DTS system can be implemented at different locations. Furthermore, by upgrading the gears of the APD the limit of the detection may be improved.
7 References


[34] Semrock, “Semrock - Part Number: FF01-550/88.”


[43] “Raman Spectroscopy - A Tutorial_php.”.


8 Appendix

8.1 FigurecreationC.m

clear;clc;close all

fig = figure('Name','Temperature','Position',[50 420 813 375]);
fig.Color = 'w';
ax = axes('Position',[ 0.08 0.13 0.9 0.8 ]); ax.Title.String = 'Ratio'; ax.Title.FontWeight = 'bold'; ax.FontSize = 12;
xlabel('Distance of Heated Region (m)','FontSize',12);
ylabel('Intensity (a.u.)','FontSize',12);
ylim([0.05 0.25]);
xlim([0 0.5]);

color = {[0.5 0 0.5],[0.1 0 0.6],'b','c',[0 0.5 0.5],'g',[0.25 0.75 0],[0.94 0.89 0.21],[.98 .61 .21],'r',[0,0,0]};

hold(ax,'on');

mid = zeros(19,1);
mii = ones(19,1);
maa = zeros(19,1);

% Finds the median of the data set at the smallest resolvable leg
for f = 2:12
    fn = sprintf('Temp%d4.mat',f);
    load(fn)
    X = C.(sprintf('T%d4',f));
    Y = X(621:721,2);
    X = X(621:721,1) - 3.145;
    graph = plot(X,Y,'b','LineWidth',2,'Color',color{f-1});
    mid= mid + Y(32:74,1);
    hold on
end

mid = [X(32:74,1) mid./11];

leg=legend({'24.6^{o}C','34.6^{o}C','44.5^{o}C','54.1^{o}C','64.4^{o}C','74.5^{o}C','84.1^{o}C','94.4^{o}C','104.5^{o}C','114.6^{o}C','124.7^{o}C'});

[ miny, minx ] = min(mid(:,2));
minx2 = mid2((minx2))

[ maxy, maxx ] = max(mid(:,2));
maxx = mid((maxx));

point10 = ((maxx)-(minx))*0.1+(minx) ;
point90 = ((maxx)-(minx))*0.9+(minx);
spatialres = point90-point10
bx = axes('Parent', fig, 'Position', [0.134375 0.616724738675958 0.2 0.3]);
hold(bx,'on')
bx.YLim = [0.0700 0.1070];
bx.XLim = [0.15 0.35];
zoomin = plot(mid2(:,1),mid2(:,2),'Color','b','LineWidth',1.5);

box = annotation(fig,'rectangle');
box.Position = [0.1390625 0.625435540069687 0.194270833333333 0.303135888501742];
box.LineStyle = '--';
box.LineWidth = 1.75;
box.Color = [0.85 0 0];

% puts a line where the 90 and the 10 are located
line10 = plot([point10 point10],[miny-.001 maxy+.001],'Color','k','LineStyle','--','LineWidth',1.25);
line90 = plot([point90 point90],[miny-.001 maxy+.001],'Color','k','LineStyle','--','LineWidth',1.25);
spat = annotation(fig,'doublearrow',[0.211458333333333 0.28525],[0.801393728222996 0.801951219512195],[0.813937282222996 0.8019512195121951295]);

box2 = annotation(fig,'rectangle');
box2.Position = [0.3807 0.195121951219512 0.329716666666667 0.336236933797909];
box2.LineStyle = '--';
box2.LineWidth = 1.75;
box2.Color = [0.85 0 0];

arrow = annotation('arrow',[0.429033333333333 0.333854166666667],[0.535459233449477 0.822296515679444],[0.85 0 0],...
'LineWidth',1.25);
textres = annotation('textbox','String',sprintf('%0.1f cm',spatialres*100),...
'Position',[0.2325 0.809982578397213 0.07 0.0600000000000001],'
'Color','k','FontSize',10,...
'LineStyle','none');
textmin = annotation('textbox','String','10%',...
'Position',[0.181354166666667 0.658850174216028 0.0200000000000001 0.03],'
'Color','k','FontSize',10,...
'LineStyle','none');
textmax = annotation('textbox','String','90%',...
'Position',[0.2915625 0.819006968641115 0.02 0.029999999999999999],'
'Color','k','FontSize',10,...
'LineStyle','none');

saveas(fig,'Ratio.png')
8.2 FigurecreationC1.m

```matlab
fig = figure('Name','Temperature','Position',[1050 420 813 375]);
fig.Color = 'w';
ax = axes;
ax.Title.String = 'Stokes';ax.Title.FontWeight = 'bold';ax.FontSize = 12;
xlabel('Distance of Heated Region (m)','FontSize',12);
ylabel('Intensity (a.u.)','FontSize',12);
ax.Position = [ 0.08 0.13 0.9 0.8 ];

color = {{[0.5 0 0.5],[0.1 0 0.6],'b','c',[0 0.5 0.5],'g',[0.25 0.75 0],[0.94 0.89 0.21],[.98 .61 .21],'r',[0,0,0]});

hold on

mid = zeros(41,1);
mi = zeros(41,1);
maa = zeros(41,1);
for f = 2:12
    fn = sprintf('Temp%d4.mat',f);
    load(fn)
    X = C1.(sprintf('T%d4',f));
    Y = X(622:720,2);
    X = X(622:720,1)*10^8-3.15;

    [ mi(f-1,1), minpos(f-1,1) ] = min(Y(1:25));
    [ ma(f-1,1), maxpos(f-1,1) ] = max(Y(minpos(f-1,1):25));
    maxpos(f-1,1) = minpos(f-1,1) + maxpos(f-1,1) -1;
    refpoint(f-1,1:2) = [ X(minpos(f-1,1)) mi(f-1,1) ]
    norpoint(f-1,1:2) = [ X(maxpos(f-1,1)) ma(f-1,1) ]
    reslimit(f-1,1) = (norpoint(f-1,1) - refpoint(f-1,1))*0.1 + refpoint(f-1,1)
    reslimit(f-1,2) = (norpoint(f-1,1) - refpoint(f-1,1))*0.9 + refpoint(f-1,1)
    spatialres(f-1,1) = reslimit(f-1,2) - reslimit(f-1,1)

    graph = plot(X,Y,'b','LineWidth',2,'color',color{f-1});
    sum(spatialres(f-1,1))/11
end

leg=legend({'24.6\degree C','34.6\degree C','44.5\degree C','54.1\degree C','64.4\degree C','74.5\degree C','84.1\degree C','94.4\degree C','104.5\degree C','114.6\degree C','124.7\degree C'});
leg.Location = 'SouthEast';

saveas(fig,'Stokes.png')
```
8.3 FigurecreationC2.m

fig = figure('Name','Temperature','Position', [1050 420 813 375]);
fig.Color = 'w';
ax = axes;
ax.Title.String = 'Ratio';ax.Title.FontWeight = 'bold';ax.FontSize = 12;
xlabel('Distance of Heated Region (m)', 'FontSize', 12);
ylabel('Intensity (a.u.)', 'FontSize', 12);
ax.Position = [0.08 0.13 0.9 0.8];

hold on

mid = zeros(41,1);
mii = zeros(41,1);
maa = zeros(41,1);

for f = 2:12

    fn = sprintf('Temp%d4.mat',f);

    load(fn)
    X = C2.(sprintf('T%d4',f));
    Y = X(621:721,2)
    X = X(621:721,1)*10^8 - 3.15;

    graph = plot(X,Y,'b','LineWidth',2,'color',color{f-1});
    hold on

    mid = mid + Y(39:79,1);

end

leg=legend({'24.6^{o}C','34.6^{o}C','44.5^{o}C','54.1^{o}C','64.4^{o}C','74.5^{o}C','84.1^{o}C','94.4^{o}C','104.5^{o}C','114.6^{o}C','124.7^{o}C'});
leg.Location = 'SouthEast';

mid = [X(39:79,1) mid./11];

% finds the 100% point at the smallest resolvable feature its x and y...
...then locates the 10 and 90 % to develop the spatial resolution of the
detection system

```
[ miny, minx ] = min(mid(:,2));
[ maxy, maxx ] = max(mid(:,2));
point10 = (maxx - minx)*0.1 + minx;
point90 = (maxx - minx)*0.9 + minx;
spatialres = point90 - point10
```

```
bx = axes('Parent',fig,'Position',[0.677302407907058 0.610255640055769 0.194270833333333 0.305730357610507]);
hold(bx,'on')
bx.YLim = [0.0225 0.055];
bx.XLim = [0.19 0.35];
zoomin = plot(mid(:,1),mid(:,2),'Color','b','LineWidth',1.5);
xticks([0.18 0.22 0.26 0.30 0.34])
yticks([0.0225 0.0385 0.055])
box = annotation(fig,'rectangle');
box.Position = [0.674016980788507 0.602358429918076 0.2 0.3];
box.LineStyle = '--';
box.LineWidth = 1.75;
box.Color = [0.85 0 0];
```

```
% puts a line where the 90 and the 10 are located
line0 = plot([minx minx],[miny maxy]);
line10 = plot([point10 point10],[miny-.001 maxy+.001],'Color','k','LineStyle','--','LineWidth',1.25);
line90 = plot([point90 point90],[miny-.001 maxy+.001],'Color','k','LineStyle','--','LineWidth',1.25);
line100 = plot([maxx maxx],[miny maxy]);
spat = annotation(fig,'doublearrow',[0.689970199914473 0.806286080821039],[0.79089177931279 0.791131855309218];)
```

```
box2 = annotation(fig,'rectangle');
box2.Position = [0.248256468172485 0.198791675990154 0.329716666666668 0.691523376518597];
box2.LineStyle = '--';
box2.LineWidth = 1.75;
box2.Color = [0.85 0 0];
```

```
arrow = annotation('arrow',[0.578576010262989 0.673508659397049],[0.834305717619603 0.774795799299883],'Color',[0.85 0 0],...
    'LineWidth',1.25);
textres = annotation('textbox','String',sprintf('%0.1f cm',spatialres*100),...
    'Position',[0.715501924310455 0.780811049809113 0.07 0.0600000000000001],'Color','k','FontSize',10,...
    'LineStyle','none');
textmin = annotation('textbox','String','{10%}',...
    'Position',[0.698352242356211 0.653015868498407 0.02000000000000002 0.03],Color','k','FontSize',10,...
    'LineStyle','none');
textmax = annotation('textbox','String','{90%}',...
    'Position',[0.813050633418857 0.710488882293388 0.01999999999999999 0.02999999999999999],Color','k','FontSize',10,...
    'LineStyle','none');
saveas(fig,'RatioStokes.png')
### Table 9 Estimated Spatial Resolution at 100 m

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<tr>
<th>Length of fiber (m)</th>
<th>SR (cm)</th>
<th>Length of fiber (m)</th>
<th>SR (cm)</th>
<th>Length of fiber (m)</th>
<th>SR (cm)</th>
<th>Length of fiber (m)</th>
<th>SR (cm)</th>
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<td>30.5</td>
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<td>45</td>
<td>7.318</td>
<td>59.5</td>
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