6.5 CW FIBER LASER ABSORPTION SPECTROMETER FOR O_2 COLUMN MEASUREMENTS IN SUPPORT OF THE ASCENDS MISSION

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1. INTRODUCTION

ITT, along with our partners at NASA LaRC, Atmospheric and Environmental Research Inc. (AER), and the University of New Hampshire, are developing an O_2 Laser Absorption Spectroscopy (LAS) instrument to satisfy the requirements of the Active Sensing of Carbon Dioxide (CO_2) over Nights, Days and Seasons (ASCENDS) mission as set forth by the National Research Council's Decadal Survey; NRC (2007).

The purpose of the O_2 lidar is to provide co-located surface pressure measurements to enable conversion of CO_2 column measurements to CO_2 mixing ratio. The team has chosen the 1.27um band of O_2 to make these measurements in order to take advantage of reduced atmospheric backscatter, and low sensitivity to relative humidity and temperature.

During 2007 and 2008, ITT succeeded in demonstrating a set of low power horizontal ground-based O_2 measurements using the same receiver used for our CO_2 system. The existing instrument has been developed and operationally validated for CO_2 measurements through multiple airborne field campaigns since 2004, using a combination of investments developed by ITT and NASA. Since the initial measurements of O_2, ITT has been internally funding the development of an advanced Fiber Raman Amplifier (FRA). This effort is in collaboration with the University of Arizona, and aims to produce the powers required to demonstrate this measurement from an Aircraft and to scale it to space.

This paper will review the instrument architecture used for CO_2 and O_2 measurements and discuss the measurements to date. Evolution of the first generation FRA and future plans will also be discussed.

2. OVERVIEW OF ITT'S CW LASER ABSORPTION SPECTROSCOPY INSTRUMENT

The architecture for the CO_2 LAS instrument for ASCENDS is illustrated in Figure 1. The all fiber-coupled transmitter consists of N distributed feedback lasers (DFB's), N modulators or semi conductor amplifiers (SOA's), and N erbium doped fiber amplifiers. Each continuous wave (CW) laser wavelength is modulated with its own RF frequency and transmitted simultaneously. A lock-in method is used to separate the wavelengths in the return measurement signal as well as the transmitted energy reference signal.

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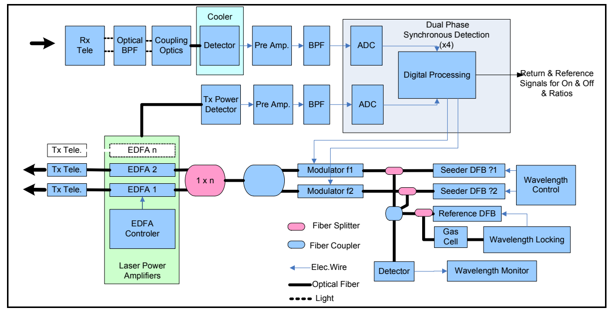

Figure 1: ITT's CO2 LAS has been operationally validated via extensive ground and aircraft campaigns and is TRL 6

This operationally validated and mature architecture offers several critical advantages in terms of ability to retrieve CO_2 Mixing Ratio, while simultaneously minimizing program risk and cost:

- Co-Located measurements of CO_2, O_2 and Altimeter, reduces significant sources of bias and errors in retrieval of CO_2 mixing ratio.
- Simultaneous transmission of all wavelengths eliminates a significant source of error from fast changes in target reflectivity; converts most natural and man-made noise terms to common mode noise which is removed when the ratio's are taken; and relaxes spacecraft pointing and jitter requirements.
- Robust all fiber laser transmitters operating in continuous-wave mode increases laser transmitter reliability an order of magnitude, while reducing cost.
- A single common detection chain for CO_2 and O_2 (using RF modulation to separate wavelengths) eliminates sources of bias and/or drift in retrieval of mixing ratio, which arise in other instruments that use separate optical paths, detectors, and electronics.
- A large-area HgCdTe APD provides gain of ~1000 with a unity excess noise factor.
- Non-diffraction limited, incoherent receiver which enables multiple low-cost fiber-coupled telescopes; enabling several meters of equivalent area at low cost.
- Multiple fiber amplifiers for CO_2, O_2 and Laser Altimeter with independent, but co-aligned outputs. Enables functional redundancy at low cost.
- Lock-in detection meets the mission requirements without the complexity and cost of coherent detection. Lock-in is significantly less sensitive to background noise than Direct Detection.

The additional components for the O_2 function for ASCENDS are shown in Figure 2. The architecture for the transmitter subsystem for the O_2 LAS instrument for ASCENDS is the same as the CO_2, instrument and shares the complete receiver including detector, electronics and signal processing.

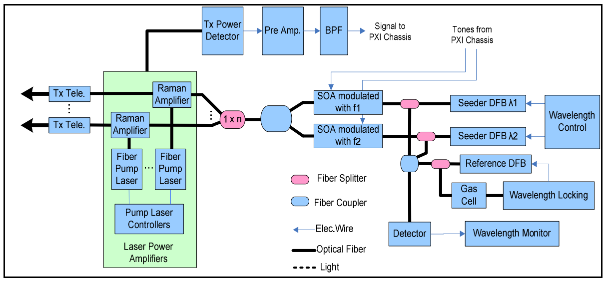

Figure 2: O2 specific components that will be added to the existing CO2 LAS instrument

Note that Figure 2 shows all of the components required for adding the O_2 module. However, many of the components are identical in function and form to those used for the validated CO_2 instrument, the only difference being the operating wavelength. The main variation is that the O_2 module will use a fiber Raman amplifier which is pumped by an Yb fiber amplifier, rather than the Erbium Doped Fiber Amplifier (EDFA) used for the CO_2 system. More detailed information regarding the instrument and validation efforts can be found in; Browell (2008), Dobbs (2007, 2008), Harrison (2008).

3. FIELD MEASUREMENTS OF O_2

The online absorption feature used in the initial O_2 LAS experiment was at a vacuum wavelength of 1271.7074 nm at the peak. This transition was chosen to have sufficient line strength for ground or aircraft based measurements. It also has minimal interference from other atmospheric species, and it has a weak dependence on temperature. The offline wavelength used was at a vacuum wavelength of 1271.817nm. A plot from the HITRAN database, showing the absorption features of both water vapor and O_2 in this region is shown in Figure 3. Several other lines more suitable for space applications have been identified by our team for example the trough shown in Figure 4. As described by Korb (1983), a measurement using the trough between two strong lines increases the sensitivity to pressure changes while decreasing sensitivity to laser frequency jitter and drift. An O_2 LAS using this trough is identical in implementation to those carried out in this study. The only difference is the wavelength of the seed laser and the necessary components for this have already been identified or obtained by ITT.

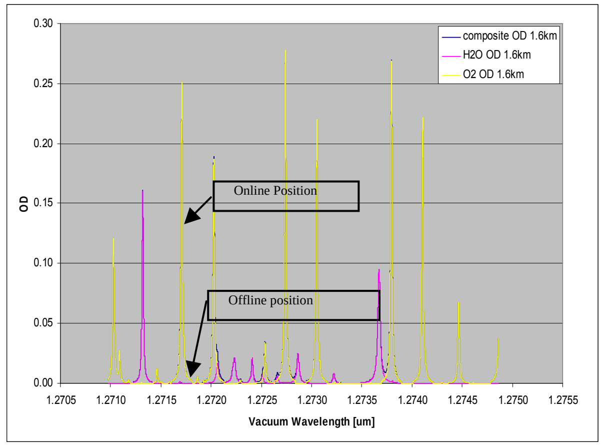

Figure 3: HITRAN (04) spectra for O2 and H2O for a 1.6 km path with standard atmospheric conditions

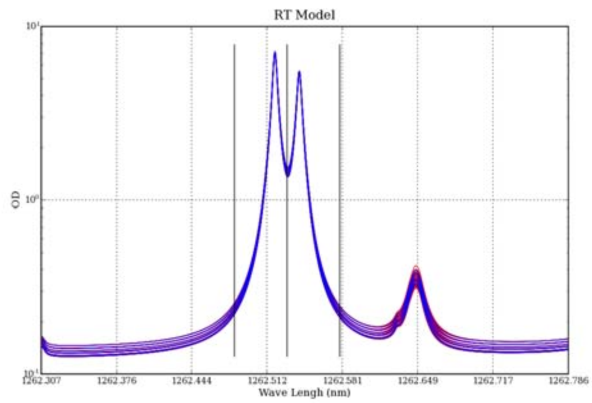

Figure 4: Trough near 1262.5 nm is excellent choice for space based measurements and decreases the sensitivity to laser frequency jitter and drift by an order of magnitude

3.1 Experimental Setup

The O_2 lidar was operated at ITT's field test site located in New Haven, IN. The instrument is housed in a trailer, which is located 680 m from a stationary target. The target consists of both light and dark surfaces, each has been shown to have fairly Lambertian reflectance profiles. The two targets allow both high and low power measurements to be conducted at this site. These facilities are illustrated in Figure 5. This test site is also equipped with instrumentation for monitoring atmospheric pressure, temperature, humidity, wind speed and direction, CO_2 in ppm and H_2O in ppt.

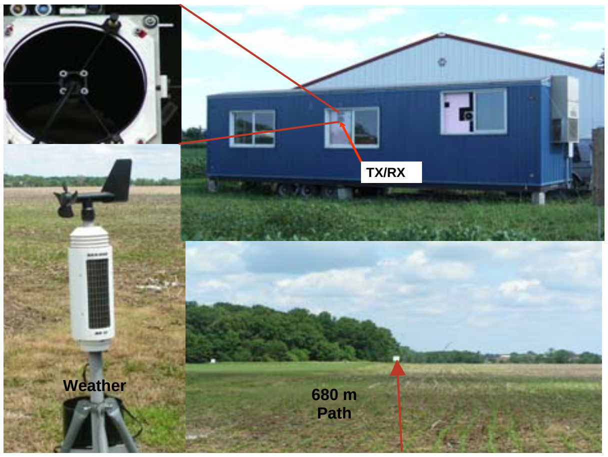

Figure 5 ITT's test facility in New Haven, Indiana

The transmitter used for the initial experiments was assembled using all commercial off the shelf (COTS) components. The first iteration of the transmitter produced only about 10mW per line (on and off). The only modification required to the CO_2 receiver was to change the optical bandpass filter used for solar rejection to include a pass-band for the 1.27μm channel. The same telescope, detector, receiver electronics and signal processing lock-in system was used. After the initial measurements in 2007, ITT integrated the low power transmitter, now capable of ~50mW per line, into the engineering development unit (EDU) flight instrument and obtained simultaneous CO_2 and O_2 ground-based measurements.

3.2 Measurements and Results

The first O_2 measurements were carried out at the ITT field site starting in June of 2007. The initial measurements included sweeps of the line center as well as adjacent lines to verify the determined setting for the DFB controllers. After verifying the line positions, several 5 – 10 minute collections were performed using different combinations of broadened linewidths (8MHz, 550 MHz and 1.1GHz). These linewidths were chosen after significant experimentation was carried out to determine the most efficient means of obtaining a flat power spectral density of our seed lasers, in a reliable manner. The data from these measurements along with the ancillary data regarding the atmospheric state was analyzed by AER. The ancillary data was used to produce a modeled differential absorption lidar (DIAL) ratio using a realistic atmosphere and LBLRTM (Line By Line Radiative Transfer Model); Clough (2005). The modeled values were then compared to the lidar's measured values. The initial results agreed to within 5.5% between the measured and modeled DIAL ratios for measurements made using the 8 MHz linewidth for both the on and the offline. The agreement of the lidar for the cases that used a 550MHz or 1.1GHz online agreed with the modeled results to within 2.2%. This result was obtained while making measurements at the line center, which is less sensitive to pressure changes for the narrow linewidth as the density of O_2 atoms increases at the same time the line for each individual atom is broadened due to increased pressure.

Based on analysis done by AER, an optimal position for sensitivity to pressure, for the line we are using on a horizontal path length, was determined to be centered at a vacuum wavelength of 1271.716 nm. Further measurements were conducted in October and November using the new "online" (or sideline) position. These measurements showed agreements for all cases to better than 2%, and were better than 1% for the broad linewidth cases. The majority of the error in these measurements is the result of frequency jitter and laser drift of only a couple of tenths of a pm. Since these measurements were made on the steep slope of the absorption feature they are very sensitive to these drifts. The improved results using the broader linewidths are due to an effective reduction of the slope of the convolved absorption feature with the broader laser spectrum. The measurements made in 2008 with the integrated transmitter were also made using the side line position and showed similar agreement. An example of modeled versus measured data is shown in Figure 6.

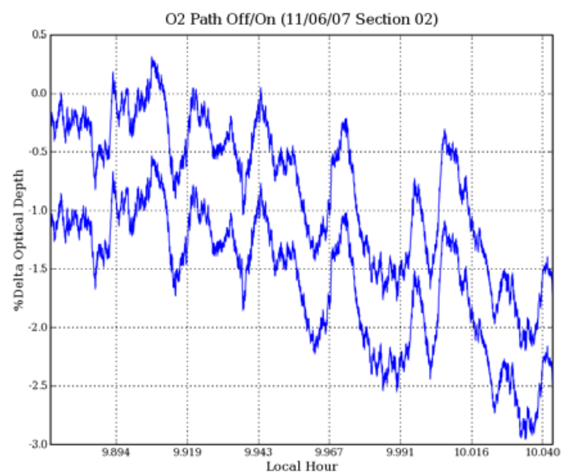

Figure 6: Example of measured O_2 versus modeled O_2 optical depth using independent weather station data from two nearby locations

Unfortunately, the wavelength reference available for these initial measurements was only accurate to ~ 0.5pm, which prevented us from tracking the smaller frequency drifts and is the most likely source of the drift in the measurement shown.

Future measurements will be made using the trough shown in Figure 4, which reduces the error from frequency drifts by more than an order of magnitude and should result in measurements which agree to within 0.2 to 0.1%. Alternatively, an accurate wavelength reference could be used, since the software developed by AER can use the precise knowledge of the transmitted wavelengths to produce modeled results that track the laser frequency as is done for the CO_2 measurements.

4. RAMAN AMPLIFIER FOR O_2 LIDAR

The development of optical fiber Raman amplifiers offers the remote sensing community access to wavelengths which are not presently available in conventional solid state lasers or fiber lasers/amplifiers.

Based on the nonparametric nonlinear process of stimulated Raman scattering (SRS) within optical fiber, FRAs have until recently been restricted in their application due to competing nonlinear effects such as stimulated Brillioun scattering (SBS), self phase modulation (SPM), and four wave mixing (FWM), which limit the over all optical gain that can be achieved. Of these effects, SBS is the most problematic because of its relatively lower power threshold as compared to SRS for narrowband light; Aoki (1989). As such, much research has been done to increase the natural Raman gain in optical fibers using germanosilicate glasses; Dianov (1995), Grubb (1994), Nakashima (1985), and to suppress SBS by various physical techniques; Broderick (1999), Hansryd (2001), Shiraki (1995,1996), Yoshizawa (1993). Most of these techniques; however, are not robust and have limited efficiency when used with fibers for high power Raman amplification of very narrowband light sources as needed in several remote sensing applications.

Because SBS is the result of a longitudinal refractive index modulation along the fiber due to acoustic waves created by electrostriction; Agrawal (2001), several researchers recently (2005) have proposed new optical fiber designs that allow the acoustic phonons that cause SBS to be separated spatially within the fiber from the optical fields associated with SRS; Dragic (2005). Since this initial paper, further research has been carried out by Corning Inc. to apply such fiber designs to high power rare-earth doped fiber lasers and amplifiers; Kobyakov (2005), Li (2007), Ruffin (2005), Walton (2006). Because the reduction in SBS that will occur within these fibers is independent of the spectral bandwidth and power of the optical fields, the potential for high efficiency, high power, narrow linewidth, robust FRAs is tremendous. With this new fiber design concept, ITT is currently developing, in conjunction with the University of Arizona and using internal funding, a first generation FRA for an O_2 LAS system. Figure 7 below shows a schematic representation of the first generation Raman amplifier design.

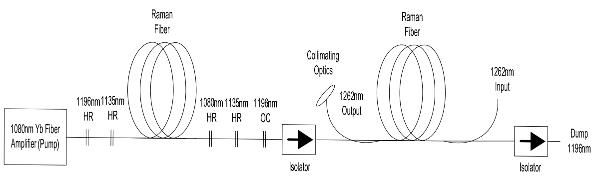

Figure 7: Generation I FRA design schematic based on GeO_2 as primary dopant, HR-High Reflector OC-Output Coupler

Over the course of the 2008 calendar year 3 fiber designs for suppressing SBS while maintaining maximum Raman gain were completed by the University of Arizona. Corning began manufacturing two of the designs in July. Recently, fiber has been fabricated for one of the designs and is currently being evaluated and will then be integrated into the first fiber amplifier. The amplifier will be completed and tested in early 2009. The concept for the design is to structure the fiber to separate the optical and acoustic modes, thus reducing the overlap and increasing the SBS threshold, while simultaneously structuring the fiber for maximum Raman gain.

The new fiber, designed by the University of Arizona based on ITT's specifications and manufactured by Corning Specialty Fibers, for this first generation amplifier uses GeO_2 doping of silica (germanosilicate) glass. While the primary Raman Stokes' shift found in germanosilicate glasses is ~450 cm^{-1}; Aoki (1989), an amplifier built for ~1270nm using a 1080nm ytterbium fiber source as the initial pump source will require multiple Raman stages (three). The first generation amplifier using germanosilicate glass fiber thus employs a cascaded Raman resonator (i.e. laser) pumped in the backward direction by a ytterbium fiber amplifier as the first two stages followed by a 1270nm single pass amplification stage, as seen in Figure 7.

Because a multiple stage amplifier is not optimal for achieving maximum efficiency, a second generation single stage amplifier is being developed, under a NASA Advanced Component Technology grant, to achieve the specifications required for the ASCENDS mission. This second generation amplifier will be created leveraging insight gained in the current generation, with a fiber design similar to that developed in the first generation but with P_2O_5 instead of GeO_2 as the primary dopant. Since P_2O_5 has a significantly larger Raman Stokes' shift of ~1300 cm^{-1}; Gabriagues (1989), multiple Raman stages are unnecessary to convert a 1080nm pump source into 1262nm light by SRS. Employing a single stage in the FRA thus results in a more reliable, efficient and compact transmitter design.

5. SUMMARY AND CONCLUSIONS

Low power demonstration of an O_2 lidar that shares the receiver with ITT's demonstrated CO_2 lidar, has been completed and shows agreement to within ~2% of modeled values based on *in situ* data from two local weather stations. The main element limiting the accuracy of these measurements was the resolution of the wavelength reference used. The addition of an accurate wavelength reference and exploiting the benefits of making the measurements in a trough between two strong lines is expected to improve these results to about a tenth of a percent. Furthermore, a robust set of processing tools has been developed for full retrievals of O_2 optical depth and pressure retrievals.

ITT is actively pursuing the development of an efficient Raman amplifier capable of measuring O_2 from a space based platform. All of the required components have been obtained and the first generation of an SBS suppressed fiber Raman amplifier will be demonstrated in early 2009. Aircraft demonstrations of the low power O_2 lidar are also planned for early 2009. The second generation amplifier will use a single stage design producing a more compact and efficient amplifier. We are currently on track to have the Gen II amplifier built, tested and to complete a high power flight demonstration by the end of 2009.

6. REFERENCES

Agrawal G.P., "Nonlinear Fiber Optics", *3rd Edition Academic Press*, 264, San Diego, (2001).

Aoki Y., "Fibre Raman amplifier properties for applications to long-distance optical communications", *Optical and Quantum Electron.* 21, S89 (1989).

Broderick N.G.R., Offerhaus H.L., Richardson D.J., Sammut R.A., Caplen J., and Dong L., "Large mode area fibers for high power applications", *Opt. Fiber Technol.* 5(2), 185 (1999).

Browell, E V, Dobbs, M E, Dobler, Kooi, S, Choi, Y., Harrison, F W., Moore, B., Zaccheo, T S, "First Airborne Laser Remote Measurements of Atmospheric Carbon Dioxide", Amer. Geo. Pys. Union Fall Meeting, S. F., J A41D-0145, CA Dec. 15-19, 2008.

Clough, S. A., Shephard M. W., Mlawer E. J., Delamere J. S., Iacono M. J., Cady-Pereira K., Boukabara S., and Brown P. D., Atmospheric Radiative Transfer Modeling: a Summary of the AER Codes. *J. Quant. Spectrosc. Radiat. Transfer*, **91**, 233-244, (2005).

Dianov E.M., Abramov A.A., Bubnov M.M., Prokhorov A.M., Shipulin A.V., Devjatykh G.G., Guryanov A.N., and Khopin V.F., "30dB gain Raman amplifier at 1.3μm in low-loss high GeO_2-doped silica fibres", *Electron. Lett.* 31(13), 1057 (1995).

Dobbs M., Sharp W., Browell E. V., Zacheo S., Moore B., "A Sinusoidal Modulated CW Integrated Path Differential Absorption Lidar for Mapping Sources and Sinks of Carbon Dioxide from Space", *14th Coherent Laser Radar Conference,* Snowmass, CO, July 8*,* presentation #26, (2007).

Dobbs M., Dobler J., Braun M., McGregor D., Overbeck J., Moore B., Browell E., and Zaccheo T.S., A Modulated CW Fiber Laser-Lidar Suite for the ASCENDS Mission *Proc. 24th International Laser Radar Conference,* Boulder, CO, June 23-27, (2008).

Dragic P.D., Liu C.H., Papen G.C., and Galvanauskus A., Optical Fiber with an Acoustic Guiding Layer for Stimulated Brillouin Scattering Suppression, *CLEO 2005*, CThZ3 (2005).

Gabriagues J.M., "Non linear effects for light generation and amplification in optical fibers", Proc. SPIE 1171, 43 (1989).

Grubb S.G., Erdogan T., Mizrahi V., Strasser T., Cheung W.Y., Reed W.A., Lemaire P.J., Miller A.E., Kosinski S.G., Nykolak G., and Becker P.C., "1.3μm Cascaded Raman Amplifier in Germanosilicate Fibers", *Proceedings of Optical Amplifiers and Their Applications*, vol.14, Paper PD4 (1994).

Gray S., Walton D., Wang J., Li M.J., Chen X., Ruffin A.B., Demeritt J., Zenteno L., "High power, narrow linewidth fiber amplifiers", *Proceedings of Optical Amplifiers and Their Applications*, vol. , Paper OSuB1 (2006).

Hansryd J., Dross F., Westlund M., Andrekson P.A., and Knudsen S.N., "Increase of the SBS Threshold in a Short Highly Nonlinear Fiber by Applying a Temperature Distribution", *J. Lightwave Technol.* 19(11), 1691 (2001).

Harrison F., Browell E., Boland S., Spiers G, "A Feasiblity Assessment of Implementing the Active Remote Sensing of CO_2 Emissions Over Nights, Days, And Seasons (ASCENDS) Mission", *Proc. 24th International Laser Radar Conference,* Boulder, CO, June 23-27, (2008).

Kobyakov A., Khumar S., Chowdhury D.Q., Ruffin A.B., Sauer M., Bickham S.R., and Mishra R., "Design concept for optical fibers with enhanced SBS threshold", *Opt. Express,* 13(14), 5338 (2005).

Korb, L. C. and Weng C. Y., "Differential absorption lidar technique for measurement of the atmospheric pressure profile", *Applied Optics*, Vol. 22, No 23, December 1, (1983).

Li M.J., Chen X., Wang J., Gray S., Liu A., Demeritt J.A., Ruffin A.B., Crowley A.M., Walton D.T., and Zenteno L.A., "Al/Ge co-doped large mode area fiber with high SBS threshold", *Opt. Express* 15(13), 8290 (2007).

Nakashima T., Seikai S., and Nakazawa M., "Dependence of Raman gain on relative index difference for GeO_2-doped single-mode fibers", *Opt. Lett.* 10(8), 420 (1985).

NRC, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", *The National Academies Press*, Washington, D.C., (2007).

Ruffin A.B., Li M.J., Chen X., Kobyakov A., and Annunziata F., "Brillouin gain analysis for fibers with different refractive indices", *Opt. Lett.* 30(23), 3123 (2005).

Shiraki K., Ohashi M., and Tateda M., "Suppression of stimulated Brillouin scattering in a fibre by changing the core radius", *Electron. Lett.* **31**(8), 668-669 (1995).

Shiraki K., Ohashi M., and Tated M., "SBS Threshold of a Fiber with a Brillouin Frequency Shift Distribution", *J. Lightwave Technol.* 14(1), 50 (1996).

Yoshizawa N. and Imai T., "Stimulated Brillouin Scattering Suppression by Means of Applying Strain Distribution to Fiber with Cabling", *J. Lightwave Technol.* 11(10), 1518 (1993).