All optical fiber thermal vacuum gauge

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Abstract
A new concept of an all optical, dual-fiber-based Pirani thermal vacuum gauge is proposed and demonstrated. The configuration utilizes two fibers: one that produces heat, and one that responds to the resultant thermal exchange. The temperature of the latter fiber is a function of the heat transfer through the gas in which it resides. The active heat-generating fiber is a luminescence-quenched, heavily Yb\textsuperscript{3+}-doped optical fiber that efficiently produces thermal energy when optically pumped. The temperature sensor is implemented with a conventional commercial fiber Bragg grating. Both fibers are inserted into a custom vacuum chamber whose internal pressure can be carefully controlled. Performance of the system is characterized with pressures ranging from 20 mTorr to Standard Pressure. The proposed system may also be used as a sensitive flow rate sensor.

1. Introduction

The Pirani gauge [1] is one of the most common gas pressure gauges in use today [1–10]. The gauge measures the pressure-dependent thermal conductivity of the surrounding gas within a vacuum chamber. There are several ways to implement a Pirani gauge, but most rely on the fact that the resistance of a conductive heating filament (such as platinum) changes with its temperature. A constant current is flowed through the sensor wire, and with changing gas pressure, the voltage required to maintain that current will change. More specifically, gas density, and therefore thermal transport away from the heating element, both increase with increasing pressure, lowering the filament temperature and therefore also the resistivity. Hence, a measurement of the voltage across the sensor wire gives a direct measurement of pressure. Alternatively, current flow is measured while the electrically conductive filament is heated and maintained at a constant temperature, with the varying current compensating for the heat loss due to thermal transfer to the surrounding gas. The lower the gas pressure in a vacuum chamber, the lower the current that is required to maintain the specified temperature of the filament. In this way, the gas pressure is deduced from the electrical current measurements. As the heat conductivity varies from one gas mixture to another, such pressure sensors usually are calibrated for a given mixture. The operating pressure typically ranges from 1 mTorr to 1000 Torr for commercial Pirani gauges [11, 12].

However, the electrical components in such gauges can be influenced by interference by electromagnetic noise, which can limit their usage in certain circumstances. As a result, there has been some progress in developing optical-based sensors. For instance, pressure sensing using optical fibers has drawn attention because of its robustness and reliability in extreme environments, such as in high pressure and in the presence of strong electromagnetic interference (EMI). Mechanical pressure sensing based on the change in strain and refractive index of a Fabry–Perot interferometer (FPI) or Bragg grating has shown potential and has even been commercialized [13]. McMillen et al proposed an actively heated fiber Bragg grating (FBG)-based pressure sensor using a single fiber [14]. A metal coating around the FBG absorbs pumping laser light resulting in heating, with the change in temperature being dependent on the gas pressure. Changes in the grating spectrum and, therefore, pressure, then are measured by a signal source. Liu et al attached a silicon pillar to a fiber with the pillar acting as an FPI [15]. In both works [14, 15] the transmitted signal wavelength is red-shifted when the temperature of the sensor increases.

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By implementing a heating source in the system (active method) [14, 15], the sensitivity is enhanced dramatically, compared to the passive (not actively heated) sensing technique. At higher pressure, thermal energy transfer to the gas becomes more significant (often through convective processes), which reduces the temperature, and thus blue-shifts the spectrum that is employed as the sensing vehicle. At low pressure, when the mean free path of the gas molecules is larger than the distance between the heat sink and the wall of the vacuum chamber, the shift is large compared to the high-pressure case because the mechanism of heat transfer is free molecular conduction [14].

In this report, an active dual-fiber arrangement is introduced for gas pressure sensing. One of the fibers, serving as the heating element (HE), possesses an Yb$^{3+}$-doped core that is luminescence-quenched. In other words, the concentration of Yb$^{3+}$ is such that it absorbs light but produces only heat rather than luminescence [16, 17]. The second fiber, inscribed with an FBG, serves as the thermal transport sensor. Its reflection wavelength is shifted due to the heat transferred to it from the HE via the gas in the vacuum chamber. Ease of fabrication and absence of metal parts in this all-optical thermal vacuum gauge makes the system beneficial for gas pressure sensing in harsh environments.

2. Methods

2.1. Optical fiber components

The FBG (high reflectivity near 1016 nm with wavelength arbitrarily selected) was simply a commercial off-the-shelf device (OE Land, Canada). The optical fiber comprising the heating element (the ‘active fiber’), on the other hand, was fabricated with the reactive molten core (rMC) approach [18]. Specifically, a 1 mm diameter ytterbium wire (99.9% purity, Sigma-Aldrich) was placed inside a pure sapphire (Al$_2$O$_3$) sleeve (Saint-Gobain), which measured 1.1 mm inner diameter and 1.5 mm outer diameter. This Yb wire-Al$_2$O$_3$ assembly was inserted into a pure silica capillary tube (Heraeus Tenevo Inc.) with 3 mm inner diameter and 30 mm outer diameter, which served as the fiber cladding. The fiber was drawn at a temperature of about 2050 °C and to a cladding diameter of 110 μm, during which the Yb metal oxidizes to Yb$_2$O$_3$. A conventional single UV-curable acrylate coating was applied during the drawing process yielding a fiber diameter of 250 μm. The use of the pure Yb wire significantly increased the Yb$^{3+}$ concentration (23.4% weight percent, measured via Energy Dispersive X-ray analysis) in comparison to other, more conventional Yb-doped fibers used for lasers, leading to one that, while performance limiting for laser applications, forms the basis for a very efficient optically-pumped high-temperature thermal element. The refractive index profile is shown in figure 1 and was measured transversely through the side of the fiber at a wavelength of 950 nm using a Fourier transform interferometer [19, Interfiber Analysis, LLC].

The aforementioned Yb-doped fiber was optically pumped by a commercial fiber-coupled laser diode operating near 976 nm (Lumentum Operations). A typical temperature versus time curve for the HE is shown in figure 2 for a step-wise increase in pump power at 976 nm. The HE temperature was measured with a bulk metal probe in open air with a much larger mass/volume ratio than that for the heated optical fiber. Therefore, the temperatures of figure 2 represent lower limits to the actual values, with the true temperatures likely being at

![Figure 1. Refractive index profile of the Yb-doped fiber used as a heating element.](image)
least somewhat higher. The primary reasons for a nonlinear dependence of the fiber temperature on the pump power are the heat transfer processes, which remove heat from the HE more efficiently with increasing temperature difference between the HE and ambient air.

Owing to the high Yb concentration, pump light can completely be absorbed within a few mm of the active fiber, suggesting a thermal power density on the order of $\sim 10 \text{ W nl}^{-1}$ generated in the core of the fiber. No evidence of significant Yb ($^2F_{5/2} \rightarrow ^2F_{7/2}$) emission was observed from the fiber, suggesting near-unity conversion efficiency from optical to thermal power. To implement the HE in the vacuum setup, a short segment ($\sim$ few mm) of active fiber was spliced between two passive fibers (Corning HI 1060).

### 2.2. Vacuum chamber setup

A customized acrylic-based vacuum chamber is used in the experiment as shown in figure 3 (top view) and 4 (front view). All the components are made either of polymers or ceramics. The chamber size was 10 mm in diameter and 20 mm in height, although the whole system, which includes tubing and the vacuum pump, had a much larger total volume.

A top view of the experimental setup is shown in figure 3 (not to scale). To form the chamber, a hole (10 mm in diameter) was drilled into the middle of an acrylic block, where a 2 mm sample of uncoated active fiber ($\sim$1 m pigtailed spliced on both ends) and a commercial FBG ($\sim$1 m pigtailed on both ends) were placed 1 mm apart in the radial direction. This was achieved with the aid of a pair of parallel V-grooves that were etched into the acrylic substrate. The pigtails are all single-mode fibers and are glued onto the acrylic block to hold the active fiber and
FBG in the desired position. This also helped to prevent any leakage at the points where the fibers come into the chamber. Pump light from the laser diode, operating at 976 nm, is launched into one of the active fiber pigtails (to provide heat), and one of the FBG pigtails was connected to a white light source to serve as the thermal sensor. The spectrum transmitted through the FBG was measured with an optical spectrum analyzer at the output end.

A front view of the experimental setup is provided in figure 4 (not to scale), where the laser diode, white light source, and spectrum analyzer are not shown for simplicity. The vacuum chamber was completed with a second acrylic block placed over the top of the first, sandwiching the fibers between them. O-rings then were used to seal the chamber. The chamber was connected to a scroll dry vacuum pump (Edwards NXDs10i) from the bottom, and a valve was placed at this connection to prevent air from flowing between the chamber and vacuum pump after reaching the desired vacuum level. The metal vacuum tubing between the pump and chamber had two additional components, as shown in figure 4. First, a commercial convection-enhanced Pirani vacuum gauge (Kurt J Lesker, KJL275800LL) was connected to the chamber in order to have a calibrated measurement of the internal pressure. Second, on the other side of the Pirani gauge, a variable leak valve is connected in order to precisely adjust the vacuum level.

Therefore, during the experiment, the pressure was controlled by the variable leak valve, the thermal energy generated by active fiber was controlled by the applied current to the laser diode, while the transmitted spectra were recorded for different experimental conditions with the spectrum analyzer.

3. Results and discussion

Prior to using the described setup as a vacuum sensor, the FBG transmission spectrum was measured for vacuum levels ranging from 0.02 to 760 Torr and no optical power delivered to the HE in order to verify that changes to the vacuum pressure alone did not influence the transmission spectra. They were indistinguishable for all vacuum levels, indicating that no significant force is acting on the FBG when the pressure is varied.

Figures 5–7 provide transmission spectra for the FBG as a function of pump drive current (pump power) and chamber pressure. They demonstrate the high sensitivity of the FBG to the presence of the vacuum. In all cases, a red-shifting of portions of the spectra can be observed with increasing chamber pressure. These measurements were acquired over several repeating cycles of raising and lowering the air pressure. No hysteresis was observed during this process, indicating that the sensor gives repeatable measurements. Nevertheless, the main source of error in this repeatability study was the difficulty in bringing the chamber pressure to precisely the same value during each cycle.

The spectra clearly indicate a non-uniform thermal distribution along the axial direction of the FBG, with some parts of the FBG not heating at all. More specifically, it can be seen that the red side of the spectrum appears to be rather immune to changes in pressure below a few hundred mTorr, while the blue side of the spectrum
appears to be much less sensitive to higher pressures. Calibration of the transmission spectrum to pressure would therefore involve analysis of the evolution of both the red and blue spectral sides, perhaps by integrating the outer-wavelength parts of the spectra outside of some appropriate wavelength range, either computationally, or optically by measuring the power reflected or transmitted using a broadband light source. That being said, it is important to point out that the operating principle of the proposed device is based on detecting the heat transferred between the HE and FBG through a gas medium, and that careful tracking of the FBG spectrum, outside of the initial calibration, is therefore not a critical aspect of the sensing mechanism. Due to the nature of the heat transfer processes, most of the obtained spectra exhibit nonlinear dependencies on the vacuum level, HE temperature, distance between the HE and FBG, and geometry of the HE, all of which can be degrees-of-freedom in improving the performance of the sensor. Detailed study of the physical processes taking place in the described system, and their optimization, is beyond the scope of this paper and will be discussed elsewhere.

Next, the points made in the previous paragraph are illustrated with an example. To estimate the sensor performance, the overlap between the spectra produced by the diode lasers and the FBG in transmission (figure 6) has been calculated, and are given in figure 8(a). In this way, the pressure of a vacuum chamber is determined simply by measuring an optical power transmitted through the FBG. Clearly, and as with any Pirani-style gauge, this requires careful initial calibration. For this simulation, the two hypothetical laser sources operate at 1015.7 and 1016.6 nm with Gaussian spectral distribution of 0.1 nm spectral width (FWHM). These

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**Figure 5.** Transmission spectra for the FBG as a function of pressure at 220 mW of pump power.

**Figure 6.** Transmission spectra for the FBG as a function of pressure at 370 mW of pump power.
Figure 7. Transmission spectra of the FBG, recorded over the 1015.5 - 1017.0 nm region for three values of pump diode current and four values of background pressure.

Figure 8. (a) Calculated transmission spectra of the FBG for two probing laser diodes operating at 1016.6 and 1015.7 nm and having a spectral linewidth of 0.1 nm FWHM. Pumping laser power is set to 370 mW. (b) Calculated accuracy of the pressure sensor for a 0.02–500 Torr pressure range, compared to the accuracy of a conventional Pirani Gauge commercially available from Kurt J Lesker.
wavelengths were selected by simple inspection of the pressure-dependent FBG spectra. From figure 8(a), it can be seen that the transmitted powers are asymptotic, relating to the relative response of the red or blue sides of the FBG spectrum to changes in pressure. Consequently, the former laser wavelength is used to characterize pressures in the 0.02–1 Torr range and the latter one in the 1–500 Torr range. If the stability of the two probing and one pumping lasers are assumed (conservatively) to be 2%, the resulting relative accuracy of the proposed pressure measurement technique is shown in figure 8(b).

Light from the probing diodes may be launched into the fiber using standard couplers, and the transmitted intensity can be measured with a single photodiode for each individual wavelength (probe diodes turned on individually using a simple microcontroller). Such a configuration eliminates the need for spectral measurements and, therefore, significantly reduces the cost of the sensor. Furthermore, FBGs operating around 1550 nm may be more suitable for such measurements due to the wide availability of inexpensive laser diodes in the telecommunications wavelength range.

Analogous to conventional electrical Pirani-type gauges, the sensors proposed in this manuscript can operate in two regimes: static current (variable temperature) (figures 5 and 6) and static temperature (figure 7, variable pump power). Both regimes potentially can be applicable to a given system; however further detailed investigation is required to determine the more appropriate one. This likely requires scrutiny on a case-by-case basis, as the specific pressure range, gas composition, and ambient (internal) environment can vary significantly depending on the application.

The main advantages of the proposed sensors are their simplicity, robustness, and absence of the electric/magnetic fields associated with electrical current flow, which is unavoidable in conventional pressure sensors. The system also has virtually zero sensitivity to electromagnetic interference (EMI). Therefore, such all-fiber sensors are expected to be extremely useful in harsh environments (such as those associated with strong electromagnetic fields) as well as field-sensitive devices such as magnetometers, etc, where any noise-generating electromagnetic fields are particularly undesirable.

Finally, figure 9 shows the measured transmission spectrum as a function of flow rate (in standard cubic feet per meter) at a fixed pump power. As flow increases, convection carries heat away from the system, resulting in a cooling of the ambient gas temperature near to the FBG. It can be seen that the apparatus is most sensitive at low flow rates, with the response becoming asymptotic with increasing flow rate. At high flow rates, the FBG experiences minimal heating. In the measurement shown in figure 9, the two fibers were intentionally placed in the direct air pathway. In contrast, for the pressure measurements, the fibers were installed in a small volume, with a single hole connecting this volume with the main vacuum chamber. Such a configuration eliminates the dependency of the transmission spectrum on the air flow in the chamber.

As previously mentioned, the system works not by measuring the temperature of the active fiber directly, but rather by measuring the heat transfer through the gas near to the FBG. With greater pressure, more thermal energy is transferred to the surrounding gas, which then results in the observed red-shift in the FBG spectrum. Accordingly, it can be concluded that the system works in a regime that is dominated by conductive heat transport between the two fibers. The sensitivity of the proposed vacuum gauge may be improved by positioning the active fiber and FBG closer to each other. In this case, radiative thermal transport can become a significant
contributor to the measured FBG spectrum. In the regime where radiative thermal transport dominates, the FBG measures the temperature of the active fiber, and therefore the spectrum should blue-shift with increasing pressure. In the case where both radiative and conductive processes are of comparable strength, their effects can offset one another, resulting in a degradation in the sensitivity. Our studies indicate that positioning the fibers \(\sim 200 \mu m\) apart and closer, results in unexpected FBG temperature responses (optical transmission). This includes behaviors such as frequency shifts that are not monotonic, leading to spectra that start by blue-shifting and end by red-shifting with monotonically changing pressure. This behavior is interpreted as a competition between the conductive and radiative heat transfer effects, one of which dominates at specific air pressure ranges. We observed that with \(< 200 \mu m\) spacing, the system may still be used as pressure and flow sensors (in the radiative regime) if carefully calibrated. However, this result will be discussed elsewhere.

Finally, outgassing of materials plays an important role in a vacuum sensor’s accuracy. The current setup was built from acrylic, which starts significantly outgassing at pressures below several hundred mTorr. This may be one of the reasons for the low accuracies measured at below the 100 mTorr pressure range. Therefore, building the sensor enclosure instead from vacuum-grade stainless steel is expected to improve its accuracy in the low-pressure range. With respect to the optical fibers, both of the fibers exposed to vacuum were completely stripped of their acrylate buffers. The pure silica fiber cladding glass is compatible with high-vacuum environments, so no undesirable outgassing is expected from the sensor itself.

4. Conclusion

We have proposed and demonstrated a new concept for an all-optical thermal vacuum gauge based on a dual, parallel-fiber configuration. One fiber serves as a heat source (the active fiber) while the second one is the thermal transport sensor (FBG). The fibers were spaced by \(\sim 1 \text{ mm}\) and were found to cooperatively function in a regime that exhibits insignificant radiative heat transfer. Consistent with conventional Pirani style vacuum gauges, the system can operate in two modes: constant current and constant temperature. It also was shown that this structure may act as a sensitive gas pressure or flow sensor. The FBG used in the system was a conventional commercial device, while the active fiber was a custom, specialty-fabricated Yb-doped fiber that is luminescence-quenched, efficiently producing heat when optically pumped. The temperature of the heating element is easily controlled by adjusting the pumping power. Energy is transported to the FBG sensor through the gas resulting in a red-shift that is observed in its spectrum.

By reducing the distance between the two fibers, the system could be driven into a regime dominated by radiative thermal transport, and work is currently underway to understand this mode of operation. In principle, the main difference between the two operational modes is that for wider fiber spacing the FBG is used to measure the strength of thermal transport through the gas in the vicinity of the active fiber, whereas with narrow fiber spacing, the FBG is used to qualitatively measure the temperature of the active fiber itself. Both thermal transport and HE temperature are strong functions of the gas pressure. It is postulated that in some cases one configuration may offer more sensitivity than the other.

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References

[1] von Pirani M 1906 Verh. Dtsch. Phys. Ges. 8 686–94
[2] Cuykendall T 1935 Rev. Sci. Instrum. 6 371
[3] Steckelmacher W 1951 J. Sci. Instrum. 28 10
[4] English J, Fletcher B and Steckelmacher W 1965 J. Sci. Instrum. 42 77
[5] Poultier K F 1977 J. Phys. E: Sci. Instrum. 10 112
[6] Weng P K and Shi J-S 1994 Rev. Sci. Instrum. 65 492
[7] Kumira M, Sakurai F, Ohta H and Terada T 2007 Microelectron. J. 38 171
[8] Santagata F, Lervolino E, Mele L, van Herwaarden A W, Creemer J F and Sarro P M 2011 J. Micromech. Microeng. 21 115007
[9] Kubota M, Mita Y and Sugiyama M 2011 J. Micromech. Microeng. 21 045034
[10] Wei D, Fu J, Liu R, Huo Y, Liu C, Wang W and Chen D 2019 Sensors 19 188
[11] Ellefson R and Müller A 2000 J. Vac. Sci. Technol. A 18 2568–77
[12] Bley W 2019 Pressure measurement Encyclopedia of Applied Physics (New York: Wiley)
[13] Pinet E 2011 Proc. SPIE 7753 775304
[14] McMillen B, Jewart C, Buric M, Chen D P, Lin Y and Xu W 2005 Appl. Phys. Lett. 87 234101
[15] Liu G and Han M 2015 Opt. Lett. 40 2461
[16] Paschotta R, Nilsson J, Barber P R, Caplen J E, Tropper A C and Hanna D C 1997 Opt. Commun. 136 375
[17] Burshtein Z, Kalisky Y, Levy S Z, Le Boulanger P and Rotman S 2000 IEEE J. Quantum Electron. 36 1000
[18] Tuggle M, Kucera C, Hawkins T, Cavillon M, Pan G, Yu N, Dragic P and Ballato J 2019 Opt. Mater. X 1 100009
[19] Yablon A D 2010 J. Lightw. Technol. 28 360