

Near-infrared thermal lens spectrometer based on an erbium-doped fiber amplifier and an acousto-optic tunable filter, and its application in the determination of nucleotides

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A novel spectrometer that is based on the use of the thermal lens effect for sensitive measurements of absorption in the near-IR region has been developed. In this instrument the near-IR excitation light (from 1515 to 1590 nm) was provided by an erbium-doped fiber amplifier (EDFA). An acousto-optic tunable filter (AOTF) was used to spectrally disperse the light from the EDFA. The AOTF was used in a new configuration in which, instead of the diffracted light, the transmitted light was used. The heat generated as a consequence of the absorption of the near-IR excitation beam by the sample was monitored by a He-Ne laser. The sensitivity of this spectrometer was found to be at least two to three times higher than that of conventional transmission measurements. Its application in the sensitive determination of nucleotides (adenosine, cytidine, guanosine, and thymidine) is described. © 1997 Optical Society of America

Key words: Near infrared, thermal lens, acousto-optic tunable filter, erbium doped fiber amplifier, nucleotides.

1. Introduction

Tran and Gao¹ recently demonstrated that an erbium-doped fiber amplifier (EDFA) is an excellent light source for the near-IR region.¹ It is all fiber, all solid state, and reliable, and requires little maintenance. Its spectral bandwidth is wider and its output intensity higher than the other near-IR (continuous wave) sources that are currently available.¹ The recently developed near-IR spectrophotometer,¹ based on the use of the EDFA as a light source and an acousto-optic tunable filter²⁻⁶ (AOTF) as a dispersive element, can be used for measurements that are not possible with spectrophotometers based on halogen tungsten lamps. For instance, the absorption spectrum of a 1.0M Pr³⁺ aqueous solution can be successfully measured through four sheets of paper with this spectrophotometer.¹ Unfortunately, like other transmission-based instruments, this spectrophotometer has rather low sensitivity. It is,

therefore, particularly important that a novel instrument that is based on the EDFA and the AOTF but has relatively higher sensitivity be developed. The thermal lens technique is one such possibility.

The thermal lens technique is based on the measurement of the temperature increase that is produced in an illuminated sample by nonradiative relaxation of the energy absorbed from a laser.⁷⁻⁹ Thus the absorbed optical energy is directly measured in this technique. Its sensitivity is therefore directly proportional to the intensity of the excitation light (P_0). Its relative sensitivity (RS) over those of conventional transmission measurements is given by⁷⁻⁹

$$RS = \frac{P_0(dn/dT)}{1.91\lambda k}, \quad (1)$$

where λ is the wavelength of the probe beam, dn/dT is the temperature coefficient of the index of refraction, and k is the thermal conductivity of the solvent. It is evident from this equation that the sensitivity of the thermal lens measurements will be higher if a higher intensity light source is used for excitation. With a single 980-nm-diode laser pump, the total output of the EDFA used in this work is ~20 mW. Since this output is distributed over a wavelength

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Received 2 December 1996; revised manuscript received 1 April 1997.

0003-6935/97/277059-07\$10.00/0

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range of ~ 150 nm, its highest output at a single wavelength, as dispersed by an AOTF whose efficiency is $\sim 15\%$, is only in the microwatt range. The sensitivity of the thermal lens measurements would be lower than that for conventional transmission measurement techniques when such a low-intensity light is used for excitation (even when the measurements are performed in a solvent that has high dn/dT and low k values). It is therefore essential to increase the intensity of the EDFA excitation light so that the sensitivity of the thermal lens technique will be higher than that of conventional absorption measurements.

The AOTF diffracts light at a specific wavelength when an rf signal is applied into it.²⁻⁶ Conventionally, it is this diffracted light that is used in all experiments.²⁻⁶ The intensity of this diffracted light is only a fraction of the total intensity of the incident light. The transmitted light whose intensity is much higher than the diffracted light has not been used in all cases. The most probable reason for this is the lack of spectral information on this transmitted light, i.e., its intensity distribution over wavelengths. It will be demonstrated in this paper that by appropriate calibration spectral information on the transmitted light can be obtained. This will permit the use of the transmitted beam as the excitation light for the thermal lens measurements. Because the intensity of this light is much closer to the total output of the EDFA and is much higher than the diffracted light, such use will allow the thermal lens measurements to have a higher sensitivity than that of conventional absorption measurements. The calibration method used to obtain spectral information on the transmitted light and the instrumentation development for the EDFA-AOTF-based thermal lens spectrometer will be described in the first part of the paper. Calibration of the instrument will be performed with diethylamine used as the standard. The final part of the paper will address the applications of the thermal lens technique for the determination of nucleotides, i.e., adenosine, cytidine, guanosine, and thymidine.

2. Experiment

A. Materials

Deuterium oxide (99.9 at. % D) was purchased from Cambridge Isotopes. (-)-Adenosine (99%), cytidine (99%), guanosine (98%), thymidine (99%), sodium dodecylsulfate (electrophoretic grade), diethylamine (98%) and deuterium chloride (37 wt.%, 99.5 at. % D) were purchased from Aldrich.

B. Instrumentation

The thermal lens instrument used in this work is based on the pump and probe configuration (Fig. 1). An EDFA provided the excitation light. Detailed information on the EDFA was provided in a previous publication.¹ The 980-nm pump laser diode of the EDFA was temperature controlled by an ILX Lightwave Model LDT-5412 and driven by a precision cur-

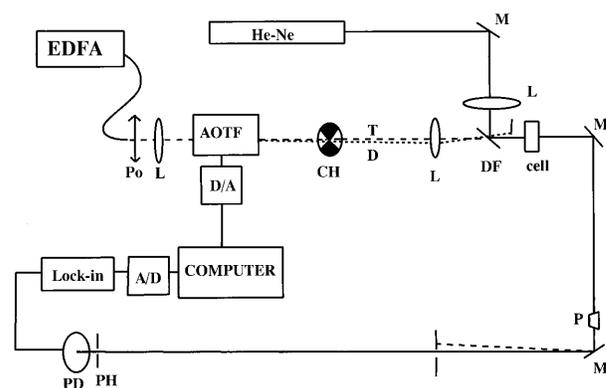


Fig. 1. Schematic diagram of the near-IR thermal lens spectrophotometer: EDFA, erbium-doped fiber amplifier; Po, polarizer; L's, lenses; AOTF, acousto-optic tunable filter; Ch, chopper; T, transmitted light; D, diffracted light; DF, dichroic filter; M's, mirrors; PD, PIN photodiode; PH, pinhole; P, prism.

rent source (ILX Lightwave Model LDX-3412). The output of the EDFA, which ranged from 1515 to 1590 nm, was collimated into the AOTF (Model AOR-IR1) for dispersion and spectral tuning. Unlike previous cases, in this study the transmitted light (T) from the AOTF was used to excite the sample, whereas the diffracted light (D) was blocked. The transmitted light, which was modulated by a mechanical chopper (Stanford Research System Model SR450) either at 20.7 Hz for the measurement of thermal lens spectra or at 4.5 Hz for the limit of detection (LOD) determination, was focused onto a quartz cell. The probe beam was provided by a red He-Ne laser (Spectra-Physics Model 105-1) that was aligned collinearly with the pump beam with a dichroic filter (DF, reflects red light). After propagating collinearly through the sample, the pump and probe beams were separated by an Amici prism (P). The intensity fluctuation in the center of the probe beam was monitored by a p-i-n photodiode (PD, United Detector Technology PIN 10-DP). The signal was demodulated and amplified by a lock-in amplifier (Stanford Research System Model SR810). The analog signal from the lock-in amplifier was acquired in a 486 IBM-compatible personal computer through a 16-bit analog-to-digital (A/D) board (National Instruments Model AT-MIO 16X) with software developed in our laboratory. The data were further treated with the GRAMS 386 program (Galactic Industries Corporation). For the measurement of the excitation light intensity as a function of wavelength the cell holder was removed and an InGaAs near-IR detector (Epitaxx Model ETX1000GR26TE) was positioned in its place.

The absorption spectra were measured on an AOTF-based near-IR spectrophotometer developed in our laboratory.^{6,10}

3. Results and Discussion

Light at a specific wavelength will be diffracted from the AOTF when an rf signal at a specific frequency is applied into the filter. The intensity of the diffracted light as a function of wavelength when light

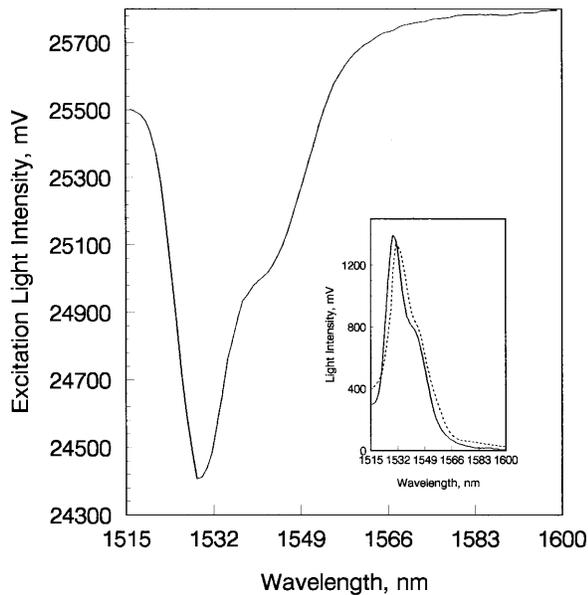


Fig. 2. Transmitted light intensity as a function of wavelength measured with an InGaAs detector. Inset, (dotted curve) intensity of the diffracted beam as a function of wavelength and (solid curve) total light intensity (i.e., intensity of light at 1600 nm) minus the intensity of the transmitted light.

from EDFA was incident into the AOTF is shown as a dashed curve in the inset in Fig. 2. As illustrated, the diffracted light in this case was only from ~1515 to 1590 nm because that is the output wavelength range of the EDFA.

It is possible to obtain the diffracted-light-wavelength relationship by measuring the intensity of the light transmitted through the AOTF because it is known that the intensity of the light diffracted from the AOTF (P_d) at a specific wavelength is dependent on the intensity of the incident light, $P(\lambda)$, and the efficiency of the AOTF $\eta(\lambda)$, at that wavelength, i.e.,²⁻⁶

$$P_d(\lambda) = P(\lambda)\eta(\lambda). \quad (2)$$

Accordingly, the intensity of the light transmitted from the AOTF at a specific wavelength is the difference between the total intensity of the incident light at all wavelengths (P_0) and the diffracted light at that wavelength (P_d)

$$P_t(\lambda) = P_0 - P(\lambda)\eta(\lambda). \quad (3)$$

Shown in Fig. 2 is the intensity of the light transmitted through the AOTF, plotted as a function of wavelength. This spectrum was obtained by placing an InGaAs detector in the focus point of the (AOTF transmitted light) pump beam. As illustrated, when an rf frequency that corresponds to the wavelength of 1600 nm was applied to the AOTF, the light transmitted through the filter was at maximum intensity. This is because the EDFA has no output light at this wavelength. Therefore no light was diffracted by the AOTF. As a consequence, light at all wave-

lengths from the EDFA output will be transmitted to give the maximum light intensity.

In fact, the light intensity at 1600 nm represents the first term on the right-hand side of Eq. (3), (P_0). For other wavelengths (from 1515 to 1590 nm) at which there is diffracted light, the intensity of the transmitted light is decreased by the amount of light diffracted out at that wavelength [second right-hand term of Eq. (3)]. For instance, when the diffracted light is maximum (around 1530 nm; see Fig. 2 inset), the intensity of the transmitted light is minimum. It is therefore possible to obtain the intensity of the diffracted light as a function of wavelength by subtracting the spectrum shown in Fig. 2 (i.e., the transmitted light intensity) from the intensity of the light at 1600 nm (i.e., the total light intensity). As expected, the spectrum obtained by such a calculation (solid curve in Fig. 2) agrees well with the diffracted light intensity profile measured directly (dashed curve in Fig. 2 inset).

The thermal lens intensity (TL) is proportional to the absorbance of the sample (Abs), the excitation laser power (P) and a proportional constant (K) that is dependent on the thermo-optical properties of the medium (i.e., dn/dT and k).⁷⁻⁹ When the sample is excited by the transmitted beam from the AOTF, the thermal lens spectrum can be described by Eq. (4)

$$TL(\lambda) = P_0K \int_{1590 \text{ nm}}^{1515 \text{ nm}} Abs(\lambda)d\lambda - KP(\lambda)Abs(\lambda). \quad (4)$$

The first term on the right-hand side of Eq. (4) represents the thermal lens signal produced when the sample is excited by the total output of the EDFA (i.e., the thermal lens signal when no light is diffracted from the AOTF or when the light corresponding to the 1600-nm setting on the AOTF is used for excitation). The second term represents the thermal lens signal produced when the sample is excited by the diffracted light. Figure 3 shows the thermal lens spectrum of diethylamine excited by the transmitted light from the AOTF. Note that the decrease in the signal observed at a specific wavelength is proportional not only to the change in excitation light intensity (by the light diffracted from the AOTF at different wavelengths) but also to the absorption of the sample at that wavelength [Eq. (4)]. As in the treatment described above to calculate the intensity of the diffracted light (Fig. 2), the thermal lens spectrum shown in Fig. 3 is subtracted from the thermal lens signal intensity at 1600 nm. The calculated thermal lens spectrum is shown in the inset of Fig. 3.

As is evident from Eq. (4), the thermal lens signal intensity is proportional to the excitation light power. Therefore, the thermal lens spectrum must be corrected to account for the change in the intensity of the excitation light at different wavelengths before it can be compared with the absorption spectrum. This

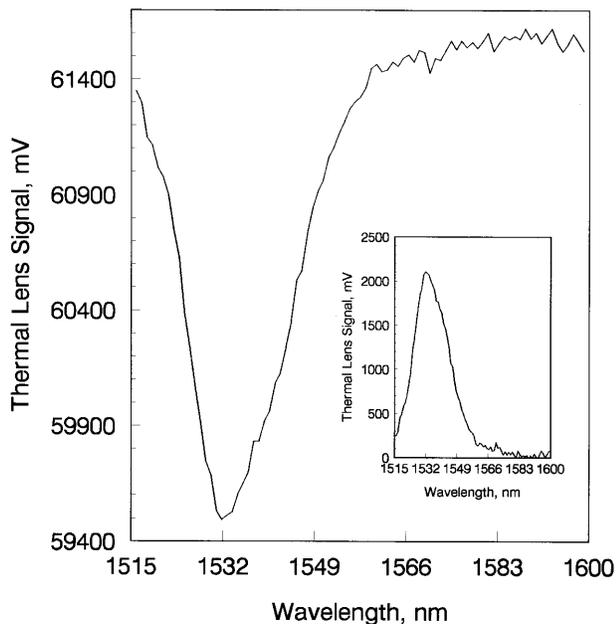


Fig. 3. Thermal lens signal of diethylamine as a function of wavelength (2-mm cell). Inset, thermal lens spectrum of diethylamine subtracted from the background.

correction is illustrated in Eq. (5), where the $CTL(\lambda)$ is the corrected thermal lens signal,

$$CTL(\lambda) = \frac{KP(\lambda)Abs(\lambda)\eta(\lambda)}{P(\lambda)\eta(\lambda)} = K Abs(\lambda). \quad (5)$$

Experimentally, such a correction was made by dividing the thermal lens spectrum of diethylamine, shown in the inset of Fig. 3, by the intensity profile of the excitation light (dotted curve in Fig. 2 inset). The corrected thermal lens spectrum, shown in Fig. 4, is similar to the absorption spectrum of the same compound measured with the AOTF-based near-IR absorption spectrophotometer. This result further confirms the effectiveness of this new thermal lens instrument and data treatment.

Subsequently the thermal lens instrument was used to determine nucleotides. Shown in Fig. 5 are the corrected thermal lens spectra of thymidine, adenosine, cytidine and guanosine. For reference, absorption spectra (from 1450 to 1700 nm) of these nucleotides, measured on the AOTF-based near-IR absorption spectrometer, are also shown in the inset. The wavelength region corresponding to those in the thermal lens spectra are highlighted. Again, the thermal lens spectra agree well with the absorption spectra for all four compounds.

The signal-to-noise ratios (S/N) of the thermal lens technique and the absorption measurements are evaluated to facilitate comparison of the sensitivity of the two techniques. Because S/N is known to depend not only on the sample concentration but also on other factors, including the solvent and the excitation laser power, it is more informative to use the slope of the calibration curve as the signal and the standard

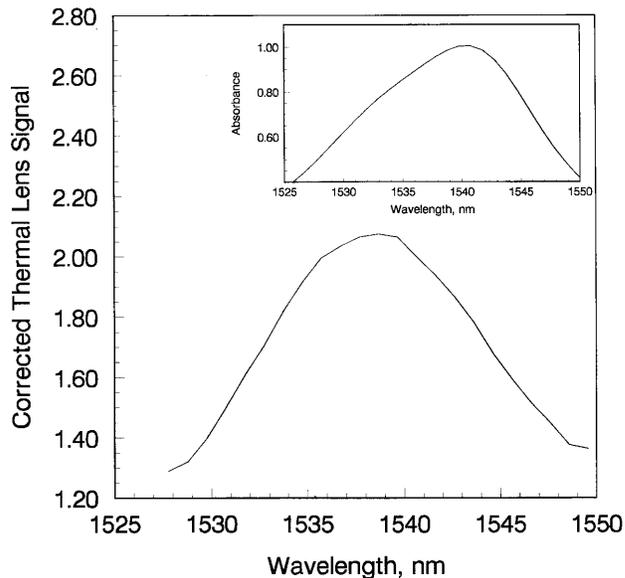


Fig. 4. Thermal lens signal of diethylamine as a function of wavelength divided by light intensity as a function of wavelength. Inset, absorption spectrum of diethylamine measured with a transmittance-based near-IR spectrophotometer (2-mm cell).

deviation of the blank signal as the noise. Table 1 lists S/N for cytidine and adenosine in D_2O and in sodium dodecyl sulfate (SDS) for the thermal lens technique as well as for conventional absorption measurements. As expected, the S/N for the thermal lens for cytidine and adenosine in D_2O is approximately two times higher than those for the absorption technique. Interesting results were observed

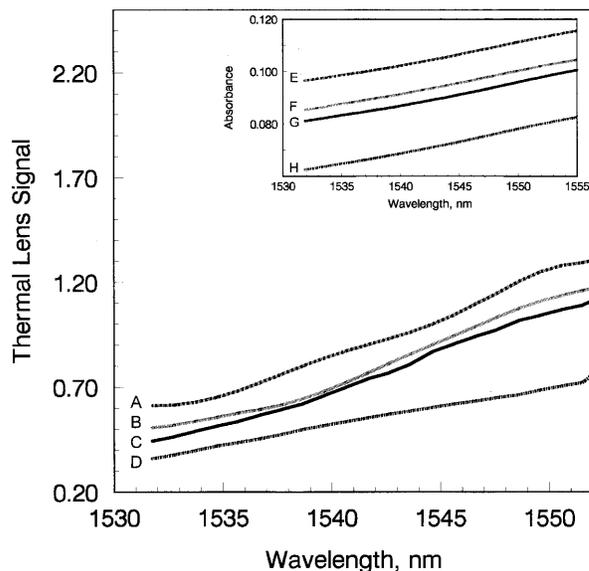


Fig. 5. Corrected thermal lens spectra of (curve D) 0.2M thymidine in D_2O , (curve C) 0.4M adenosine in 1M DCl/ D_2O , (curve B) 0.4M cytidine in D_2O , (curve A) 0.4M guanosine in 1M DCl/ D_2O . Inset, (curve H) absorbance spectra of 0.2M thymidine in D_2O , (curve G) 0.4M adenosine in 1M DCl/ D_2O , (curve F) 0.4M cytidine in D_2O , (curve E) 0.4M guanosine in 1M DCl/ D_2O .

Table 1. Signal to Noise (S/N) Ratios of the Thermal Lens Instrument and of the Absorption Spectrophotometer^a

Nucleotide (technique)	Signal ^b	Noise ^c	S/N (m ⁻¹)
Cytidine (D ₂ O) (thermal lens)	187 mV/M	0.323 mV	579
Cytidine (D ₂ O) (absorption)	0.0305 a.u./M	132 μ a.u.	231
Adenosine (D ₂ O) (thermal lens)	174 mV/M	0.431 mV	404
Adenosine (D ₂ O) (absorption)	0.0341 a.u./M	170 μ a.u.	201
Cytidine (SDS) (thermal lens)	229 mV/M	0.471 mV	486
Cytidine (SDS) (absorption)	0.0235 a.u./M	159 μ a.u.	148

^aData measured with a 1-mm pathlength cell.

^bSensitivity, i.e., slope of the calibration curve.

^cStandard deviation of the blank signal.

when 0.35M SDS was added to D₂O; that is, *S/N* for the thermal lens is increased to approximately three times higher than that of the absorption. Apparently, adding SDS leads to the increase in the signal (from 187 to 229 mV/M) as well as in the noise (from 0.323 to 0.471 mV) in the thermal lens technique. Conversely, for the absorption technique, the signal is decreased (from 0.0305 to 0.0235 a.u./M) and the noise is increased (from 132 to 159 a.u.) by the SDS. The increase in the signal of the thermal lens technique is probably due to the improvement in the thermal optical properties of the sample medium by the surfactant.¹¹ SDS increases background absorption, and as a consequence, leads to the increase in the noise level for both the thermal lens and the absorption techniques. As a consequence, *S/N* for the thermal lens is increased, whereas that for the absorption technique is decreased.

Limits of detection (LOD's) were then determined for all four nucleotides to assess the relative sensitivity of the thermal lens and the absorption techniques.

Table 2. Sensitivity, Limits of Detection (LOD's) and LOD_{abs}/LOD_{TL} of Nucleotides Measured on the Thermal Lens Spectrometer^a

Nucleotide	1533 nm		
	Sensitivity M ⁻¹	LOD M × 10 ³	LOD _{abs} /LOD _{TL}
Adenosine DCl 1M, D ₂ O	174 ± 26	4.9 ± 0.8	2.0 ± 0.3
Cytidine D ₂ O	187 ± 2	3.4 ± 0.2	2.5 ± 0.4
Guanosine DCl 1M, D ₂ O	219 ± 21	3.9 ± 0.4	1.7 ± 0.3
Thymidine D ₂ O	164 ± 5	3.1 ± 0.2	2.2 ± 0.3
1570 nm			
Adenosine DCl 1M, D ₂ O	178 ± 24	4.9 ± 0.7	1.9 ± 0.4
Cytidine D ₂ O	176 ± 2	3.8 ± 0.2	2.5 ± 0.4
Guanosine DCl 1M, D ₂ O	220 ± 21	4.0 ± 0.4	1.8 ± 0.3
Thymidine D ₂ O	167 ± 10	2.7 ± 0.2	2.6 ± 0.4

^aMeasured with a 1-mm path length cell.

Table 3. Limits of Detection (LOD's) of Cytidine Measured on the Thermal Lens Spectrometer

Conditions	1533 nm		
	Sensitivity M ⁻¹	LOD M × 10 ³	LOD _{abs} /LOD _{TL}
D ₂ O, 1-mm cell	187 ± 2	3.4 ± 0.8	2.5 ± 0.4
D ₂ O, 2-mm cell	394 ± 7	2.0 ± 0.1	2.1 ± 0.2
SDS 0.35M 1-mm cell	229 ± 5	4.1 ± 0.1	3.3 ± 0.5
SDS 0.35M 2-mm cell	440 ± 14	2.4 ± 0.2	2.8 ± 0.4
1570 nm			
D ₂ O, 1-mm cell	176 ± 2	3.8 ± 0.2	2.5 ± 0.4
D ₂ O, 2-mm cell	393 ± 9	2.3 ± 0.1	2.1 ± 0.3
SDS 0.35M 1-mm cell	240 ± 8	4.1 ± 0.3	3.3 ± 0.5
SDS 0.35M 2-mm cell	435 ± 12	2.4 ± 0.2	2.8 ± 0.3

The LOD is defined as twice the peak-to-peak noise of the baseline divided by the slope of the calibration curve. For reference, in addition to the LOD values, Table 2 also lists sensitivity values (i.e., the slopes of the calibration curves). To facilitate comparison between the two techniques, the ratio of LOD values for the absorbance technique (i.e., LOD_{abs}, measured on the AOTF-based absorption spectrometer) and the LOD for the thermal lens technique (LOD_{TL}) at two different wavelengths (1533 and 1570 nm) are also listed. Several conclusions can be drawn from this table. Specifically, the sensitivity, LOD, and LOD_{abs}/LOD_{TL} values for all four compounds remain constant, as expected, regardless of the wavelength. In general, the LOD's of the nucleotides measured with the thermal lens instrument vary from 2.7 × 10⁻³ to 4.9 × 10⁻³ M (Table 2, third column). Cytidine and thymidine provided relatively lower LOD's than guanosine and adenosine. The thermal lens technique is approximately 2 times more sensitive than the absorption technique (i.e., from LOD_{abs}/LOD_{TL}).

The effects of solvent and sample path length were also investigated by measurement of the thermal lens signal of cytidine (at two different wavelengths, 1533 and 1570 nm) in two different solvents (D₂O and SDS) and in 1- and 2-mm path-length cells. The results obtained are listed in Table 3. Again no significant change in LOD was observed when the AOTF was set at either one of these two wavelengths. It is interesting to observe that the decrease in the cuvette path length from 2 to 1 mm increased the sensitivity of the thermal lens technique compared with that of the absorption technique (fourth column of Table 3). In fact the LOD_{abs}/LOD_{TL} values increased by 19% (from 2.1 to 2.5) from the 2- to the 1-mm cuvette in D₂O. A similar effect was also observed for the SDS solutions. This is as expected, because it is known that the thermal lens signal is proportional to the excitation energy, i.e., it is inversely proportional to the spot size of the excitation beam in the sample. In this case, because a relatively short focal length

lens (5 cm) was used to focus the pump beam, the beam spot size is relatively smaller in the shorter-path-length cell (1 mm) than in the longer cell (2 mm).

Interestingly, it was found that adding 0.35M SDS to the cytidine solution leads to a 32% increase in the LOD_{abs}/LOD_{TL} value (from 2.5 to 3.3 for the 1-mm cell). Similar enhancement was also observed with the 2-mm cell (fourth column, Table 3). These results indicate that the sensitivity of the thermal lens technique is further enhanced by adding SDS to the solution. A sensitivity enhancement induced by SDS is expected because it was reported that surfactants, including SDS, increase dn/dT and decrease the thermal conductivity of the sample solution.¹¹ Furthermore, the enhancement may also be due to the fact that SDS increases the background in the absorption measurement (and hence increases the LOD for this technique), whereas the thermal lens is immune to the scattering induced by the SDS in the sample. It is noteworthy that the observed sensitivity enhancement of the thermal lens technique by SDS is of particular importance because SDS solution is often used as a medium in capillary electrophoresis for separations of nucleotides.^{12–15}

4. Conclusions

It was successfully demonstrated that a novel and sensitive near-IR thermal lens spectrometer can be developed by synergistic use of an EDFA as the light source and the transmitted beam of an AOTF for the excitation. This instrument can measure absorption spectra in the near-IR region from 1515 to 1590 nm, which covers the overtone and combination transitions of C-H, O-H, and N-H groups. Since all organic compounds including nucleotides possess one or all of these groups, they can be sensitively measured by this spectrometer. The sensitivity of this instrument is ~ 3.3 times higher than those of the conventional absorption techniques. The sensitivity can be further enhanced by a decrease in the path length of the cell or by addition of surfactants. Increasing the output power of the EDFA (by pumping it with either a higher power or with more than one 980-nm pump laser diode^{1,16,17}) would also lead to higher sensitivity because the thermal lens signal is directly proportional to the excitation laser power.

In this study the LOD's of nucleotides were determined at a single excitation wavelength (1533 or 1570 nm). Since the EDFA can be spectrally tuned from 1515 to 1590 nm, the whole thermal lens spectrum can be used for the determination. It is expected that with synergistic use of the multivariate method of calibration, e.g., the partial least-square analysis, to analyze thermal lens spectra, it may be possible simultaneously to determine samples that have multicomponents. In fact, we have previously demonstrated that simultaneous determination of the concentration of water and DMSO- h_6 in DMSO- d_6 can be accomplished by the partial least-squares method to analyze the thermal lens spectra obtained when the sample was excited by near-IR

radiation from 875 to 1050 nm light from the Ti-sapphire laser.¹⁸ Alternatively, simultaneous determination can also be accomplished in a multiplex configuration in which the sample is simultaneously excited with more than one excitation wavelength. The AOTF, with its unique properties, facilitates such determination. Specifically, we have previously demonstrated that with the AOTF used to modulate each excitation wavelength (in the visible region) at a specific frequency, the thermal lens signal obtained can be resolved into the thermal lens signals corresponding to each wavelength, thereby allowing the simultaneous determination of samples containing four different ions (Er^{3+} , Nd^{3+} , Pr^{3+} , and Sm^{3+}).¹⁹ This multivariate method of analysis and the multiplex capability of the EDFA-AOTF thermal lens technique are currently under investigation, which should help expand the application of this instrument to the area of general analysis of real-time, multicomponent samples.

The results presented in this paper also demonstrate that this thermal lens instrument is particularly suited as a detector for small-volume sample measurements, especially for micellar-mediated capillary electrophoresis, the technique often used for the separation of nucleotides.^{12–15} This is also the subject of our present intense investigation.

We are grateful to Guan Hong Gao and Wencheng Liu for their competent technical assistance and to the National Institutes of Health for financial support of this work.

References

1. C. D. Tran and G. H. Gao, "Characterization of an erbium-doped fiber amplifier as a light source and development of a near infrared spectrophotometer based on the EDFA and an acoustooptic tunable filter," *Anal. Chem.* **68**, 2264–2269 (1996).
2. C. D. Tran, "Acousto-optic devices: optical elements for spectroscopy," *Anal. Chem.* **64**, 971A–981A (1992).
3. C. D. Tran and R. J. Furlan, "Acoustooptic tunable filter as a polychromator and its application in multidimensional fluorescence spectrometry," *Anal. Chem.* **64**, 2775–2782 (1992).
4. C. D. Tran and R. J. Furlan, "Spectrofluorometer based on acousto optic tunable filters for rapid scanning and multicomponent sample analyses," *Anal. Chem.* **65**, 1675–1681 (1993).
5. C. D. Tran and J. Lu, "Characterization of the acousto optic tunable filter for the ultraviolet and visible regions and development of an acousto optic tunable filter based rapid scanning detector for high performance liquid chromatography," *Anal. Chim. Acta* **314**, 57–66 (1995).
6. M. S. Baptista, C. D. Tran, and G. H. Gao, "Near infrared detection of flow injection analysis by acousto optic tunable filter based spectrophotometry," *Anal. Chem.* **68**, 971–976 (1996).
7. C. D. Tran, "Analytical thermal lens spectrometry: past, present and future prospects," in *Photoacoustic and Photothermal Phenomena III*, D. Bicanic, ed. (Springer-Verlag, Berlin, 1992), pp. 463–473.
8. C. D. Tran, "Photothermal detectors for high performance liquid chromatography," in *HPLC Detection: Newer Methods*, G. Patonay, ed. (VCH, Deerfield Beach, Fla., 1992), pp. 111–126.
9. M. Franko and C. D. Tran, "Analytical thermal lens instrumentation," *Rev. Sci. Instrum.* **67**, 1–18 (1996).
10. M. J. Politi, C. D. Tran, and G. H. Gao, "Near infrared spec-

- troscopic investigation of inclusion complexes between cyclodextrins and aromatic compounds," *J. Phys. Chem.* **99**, 14137–14141 (1995).
11. M. Franko and C. D. Tran, "Thermal lens effect in electrolyte and surfactant media," *J. Phys. Chem.* **95**, 6688–6696 (1991).
 12. A. S. Cohen, S. Terabe, J. A. Smith, and B. L. Karger, "High performance capillary electrophoretic separation of bases, nucleosides, and oligonucleotides: retention manipulation via micellar solutions and metal additives," *Anal. Chem.* **59**, 1021–1027 (1979).
 13. T. J. Kasper, M. Melera, P. Gozel, and R. G. Brownlee, "Separation and detection of DNA by capillary electrophoresis," *J. Chromatogr.* **458**, 303–312 (1988).
 14. A. F. Lecoq, S. D. Biasi, and L. Montanarella, "Fraction collection after an optimized micellar electrokinetic capillary chromatographic separation of nucleic acid constituents," *J. Chromatogr.* **638**, 363–373 (1993).
 15. A. Loregian, C. Scremin, M. Schiavon, A. Marcello, and G. Palù, "Quantitative analysis of ribonucleotide triphosphates in cell extracts by high performance liquid chromatography and micellar electrokinetic capillary chromatography: a comparative study," *Anal. Chem.* **66**, 2981–2984 (1994).
 16. A. Bjarklev, *Optical Fiber Amplifiers: Design and System Applications* (Artech House, Boston, 1993).
 17. E. Desuvire, *Erbium Doped Fiber Amplifiers: Principles and Applications* (Wiley, New York, 1994).
 18. C. D. Tran, V. I. Grishko, and M. S. Baptista, "Nondestructive and nonintrusive determination of chemical and isotopic purity of solvents by near infrared thermal lens spectrometry," *Appl. Spectrosc.* **48**, 833–842 (1994).
 19. C. D. Tran, R. J. Furlan, and Jian Lu, "Development of a multiwavelength thermal lens spectrophotometer based on an acousto-optic tunable filter as a polychromator," *Appl. Spectrosc.* **48**, 101–106 (1994).