2209

57-km single-ended spontaneous Brillouin-based distributed fiber temperature sensor using microwave coherent detection

Sally M. Maughan, Huai H. Kee and Trevor P. Newson

Optics Letters, vol. 26, no. 6, pp. 331-333 (2001)

Optoelectronics Research Centre, University of Southampton

Southampton, SO17 1BJ, United Kingdom

Tel. +44 23 8059 4530 Fax. +44 23 8059 3149

E-mail smm@orc.soton.ac.uk

Abstract: We present a novel technique of performing single-ended distributed fiber temperature measurements using microwave heterodyne detection of spontaneous Brillouin scattering. Brillouin frequency shift measurements have been obtained for a sensing length of 57km with a spatial resolution of 20m. The rms error in frequency measurements at the far end of the sensing fiber was less than 3MHz, and the overall frequency dependence on temperature was 1.07±0.06 MHz/K.

Long-range distributed optical fiber sensors have gained increasing popularity in applications such as fire detection, monitoring of structures and the temperature profiling of power cables. The process of Brillouin scattering in optical fibers has been used extensively for the measurement of distributed temperature and/or strain, due to the dependence of both its frequency shift and power on these two measurands. The capability of distributed sensors based on Brillouin scattering to perform simultaneous measurement of both temperature and strain with low signal attenuation due to fiber losses is expected to result in Brillouin-based sensors substantially surpassing the range offered by Raman-based sensors.

The use of both stimulated and spontaneous Brillouin scattering regimes for distributed sensing have been reported, with the stimulated case requiring either access to both ends of the sensing fiber or an end reflection to achieve a counter-propagating arrangement [1][2]. With spontaneous scattering, however, access to only one end of the fiber is necessary and in this paper we focus on this type of sensor. Techniques for spontaneous Brillouin backscatter measurements fall broadly into two categories: direct detection and coherent (heterodyne) detection. In direct detection, the Brillouin signal must be optically separated from the much larger, elastic, Rayleigh component prior to detection. This has been done, for example, using Fabry-Perot [3][4] or fiber Mach-Zehnder [5] interferometers, but these optical filters must necessarily be highly stable due to the small frequency difference between Brillouin and Rayleigh components (~11GHz at 1.5μm).

Coherent detection employs a strong, narrow linewidth, optical local oscillator (OLO) which allows excellent electrical filtering of the Brillouin component as well as a greater dynamic range (since the detector photocurrent, at the beat frequency, has only a square root dependence on signal power). Signal strength is also improved, due to optical mixing with the OLO, allowing a lower gain detector to be used. To date, coherent detection of spontaneous Brillouin backscatter has been achieved by arranging for the frequency shift between the OLO and sensing pulses to be approximately equal to the Brillouin shift, bringing the Brillouin/OLO beat frequency within the bandwidth of a conventional heterodyne receiver. This frequency shift has previously been attained using a Brillouin laser [6], an acousto-optic modulator (AOM) ring circuit [7] and an electro-optic modulator (EOM)[8][9].

In this paper, we describe a novel technique for coherent detection of spontaneous Brillouin backscatter at the high frequency beat signal. Using this technique, experimental results are presented for a single-mode sensing fiber length of 57km, which is the longest sensing length reported to date. Previously, single-ended spontaneous Brillouin frequency shift measurements have been achieved using an EOM with ±1MHz accuracy over 30km of fiber with a 100m spatial resolution [9]. Double-ended stimulated measurements have exhibited 1MHz resolution over 22km of fiber with a 5m spatial resolution [10] and although similar measurements over 51km [11] have been achieved, their accuracy, in terms of the frequency shift, was not quantified.

The technique described directly measures heterodyne frequencies of ~11GHz, removing the need for an optical shifting component and allowing the use of a very simple optical configuration. There is an additional advantage over low-bandwidth coherent detection, in that variation of the Brillouin frequency shift typically a few hundred MHz for most applications, occupies only a very small proportion of the total detector bandwidth and the detector gain is almost constant to a high accuracy. Other benefits include the ability to observe both Stokes and anti-Stokes spectra independently using the same optical configuration and the flexibility over the sensing pulse characteristics and repetition rate whilst maintaining excellent frequency stability between the Brillouin signal and local oscillator signal. Since the sensitivity of such high bandwidth detectors is low, however, it is essential that the backscattered signal undergo optical amplification prior to mixing with the OLO.

The experimental configuration for the spontaneous Brillouin-based sensor is shown in Figure 1. Radiation from a pigtailed, tunable (~1520–1560nm), continuous wave laser with a linewidth 1MHz, was amplified to 10mW using an Erbium-doped fiber amplifier, EDFA 1. This radiation was then split using a 3dB coupler, with one half of the power being used to produce the OLO for heterodyne detection. The remaining power was gated through a 110MHz downshifting AOM before being amplified by EDFA 2 to produce pulses with a peak power of up to 600mW for the chosen duration of 200ns. A second 3dB coupler was used to launch 160mW pulses into the sensing fiber, allowing 50% of the backscattered light to be extracted before being further amplified by EDFA 3. The residual ASE noise was filtered by an in-fiber Bragg grating (Reflectivity = 99.4%, $\Delta\lambda$ = 0.12nm,

λ = 1533.11nm) via a circulator. The resultant signal was mixed with the OLO and detected using a 20GHz optical detector (responsivity of 35V/W). A 26.5GHz RF spectrum analyzer allows observation of the beat frequencies and, when set in zero span mode, may be used to acquire time-domain traces centered at the desired RF frequency. The polarization states of both local oscillator and pulses are continuously scrambled whilst averaging the Brillouin signal to reduce polarization noise observed on the signal. The sensing fiber comprised five sections of conventional single-mode silica fiber, which were fusion spliced together, of lengths 17500m, 17500m, 17500m, 500m and 4000m. The fiber in the fourth section was unwound from the drum (to ensure zero strain) and placed in an oven. The temperature of the oven was varied between 30°C and 60°C, whilst the rest of the fiber lengths were wound on drums and kept at room temperature (22°C).

The downshifting AOM causes the Stokes and anti-Stokes spectra to be separated in frequency by 220MHz (twice its downshift). By comparing the magnitude of the Stokes and anti-Stokes signals, it is possible to ensure that the scattering is spontaneous. The anti-Stokes spectrum was selected for the measurements with the laser tuned to 1533.2nm. Distributed spectra were obtained from 25 separate backscatter traces (each averaged 2^{12} times), taken every 5 MHz, starting at 10.84GHz. A Lorentzian curve was fitted to each spectrum using the Levenberg-Marquardt algorithm [12], and the peak frequency was evaluated.

A peak frequency plot, for an OLO power of 1.5mW at the detector, is shown in Figure 2(a), for the entire 57km fiber length; the 500m heated section at 40°C is clearly visible at the end of the fiber (separation of data points in this plot is ~200m, limited by the maximum number of data points that can be recorded in the oscilloscope). The separate fiber sections at room temperature exhibit different Brillouin frequency shifts, attributed either to differences in fiber winding tensions or to slight dissimilarity in fiber properties. The fall followed by a rise in Brillouin frequency shift at the beginning of each of the first, second and third drums of fibers is due to the portion of fiber at these ends being loosely reeled on the drums, and the following portion of the fiber being wound on the inner part of the drums. This effect was experimentally confirmed by inverting the sensing fiber, causing the resultant signal profile to be reversed. Figure 2(b) illustrates the computed rms error for selected points along the sensing fiber. It was found that the rms error in frequency shift measurement (measured over a 2km window) remained below 1MHz up to the 47km point and less than 3MHz at the far end of the sensing fiber.

In order to test the temperature response of the sensor, results were taken for the final 7km of sensing fiber only, and frequency shift measurements made for oven temperatures of 22, 30, 40, 50 and 60°C. These are shown in Figure 3(a) and result in the expected linear dependence of frequency shift with temperature (Figure 3b); the slope was found to be 1.07±0.06 MHz/K, agreeing with previously reported results [13][14].

In summary, we have demonstrated a novel spontaneous Brillouin distributed sensor using microwave heterodyne detection. These initial results provide frequency shift measurements and their dependence on temperature over a sensing length of 57km, which to our knowledge is the longest reported sensing length. An rms frequency error of 2MHz was observed at 53km (over the heated section of the sensing fiber) and a maximum rms error of 3MHz at the far end of the fiber, and the sensor spatial resolution was 20m. Combined with intensity measurements of the backscattered signal, which are currently under investigation, this sensor potentially offers simultaneous long-range monitoring of strain and temperature.

The authors wish to thank Arthur Hartog and Peter Wait for useful discussions and gratefully acknowledge the financial support provided by a link scheme in collaboration with York Sensors Ltd and Pirelli Cables Ltd.

Figure Captions:

Fig. 1. Experimental configuration of microwave coherent spontaneous Brillouin sensor; PS-Polarization scrambler, FBG-Fiber Bragg grating.

Fig. 2. (a) Measured frequency shift over the whole 57km sensing fiber length, including the heated fiber section (b) Rms error in frequency shift computed from the data in (a).

Fig. 3. (a) Variation of spontaneous Brillouin backscattered frequency shift, for the heated fiber section at 22, 30, 40, 50 and 60°C (b) Linear dependence of this frequency shift with temperature

References:

[1] T.Horiguchi, J. Lightwave Technol. **13**, 1296 (1995).

[2] M.Nikles, L.Thevenaz and P.A.Robert, Opt. Lett. **21**, 758 (1996).

[3] P.C.Wait and T.P.Newson, Opt. Comm. **122**, 141 (1996).

[4] T.R.Parker, M.Farhadiroushan, V.A.Handerek and A.J.Rogers, IEEE Photon. Technol. Lett. **9**, 979 (1997).

[5] G.P.Lees, P.C.Wait, M.J.Cole and T.P.Newson, IEEE Photon. Technol. Lett. **10**, 126 (1998).

[6] V.Lecoeuche, D.J.Webb, C.N.Pannell and D.A.Jackson, *OFS-13 Proceedings*, pp. 349-352, (Korea, 1999).

[7] K.Shimizu, T.Horiguchi, Y.Koyamada and T. Kurashima, J. Lightwave Technol. **12**, 730 (1994).

[8] K.Tsuji, K.Shimizu, T.Horiguchi and Y.Koyamada, IEEE Photon. Technol. Lett. **7**, 804 (1995).

[9] H.Izumita, T.Sato, M.Tateda and Y.Koyamada, IEEE Photon. Technol. Lett. **8**, 1674 (1996).

[10] X.Bao, D.J.Webb and D.A.Jackson, Opt. Lett. **19**, 141 (1994).

[11] X.Bao, J.Dhliwayo, N.Heron, D.J.Webb and D.A.Jackson, J. Lightwave Technol. **13**, 1340 (1995).

[12] W.H.Press, S.A.Teukolsky, W.T.Vetterling and B.P.Flannery, *Numerical Recipes in C – The Art of Scientific Computing (Second Edition)*, (Cambridge U. Press, Cambridge, 1995) p. 683.

[13] T.R.Parker, M.Farhadiroushan, V.A.Handerek and A.J.Rogers, Opt. Lett. **22**, 787 (1997).

[14] T.Kurashima, T.Horiguchi and M.Tateda, IEEE Photon. Technol. Lett. **2**, 718 (1990).

TOP

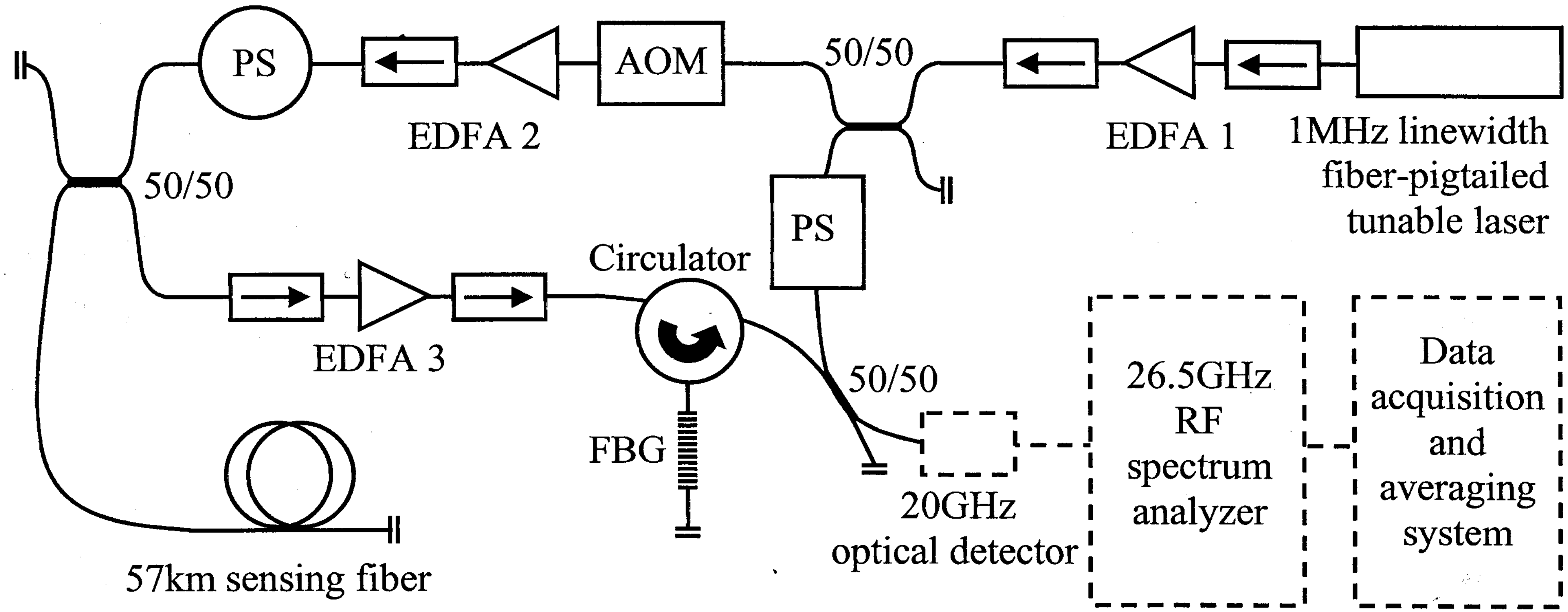
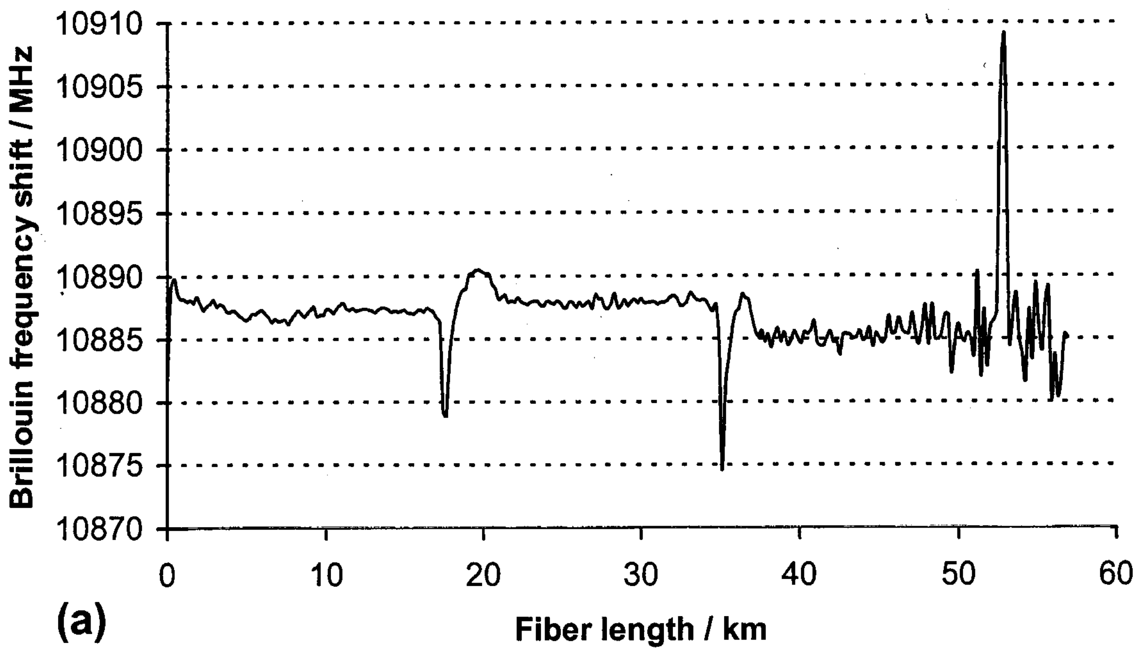
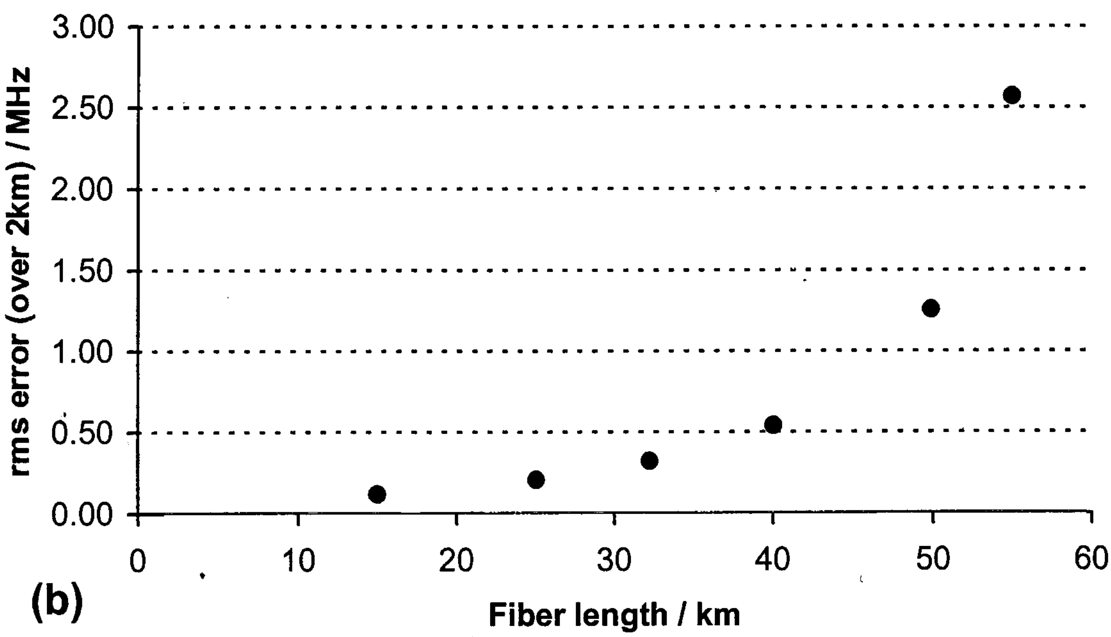


Figure 1, S.M.Maughan, Optics Letters

TOP



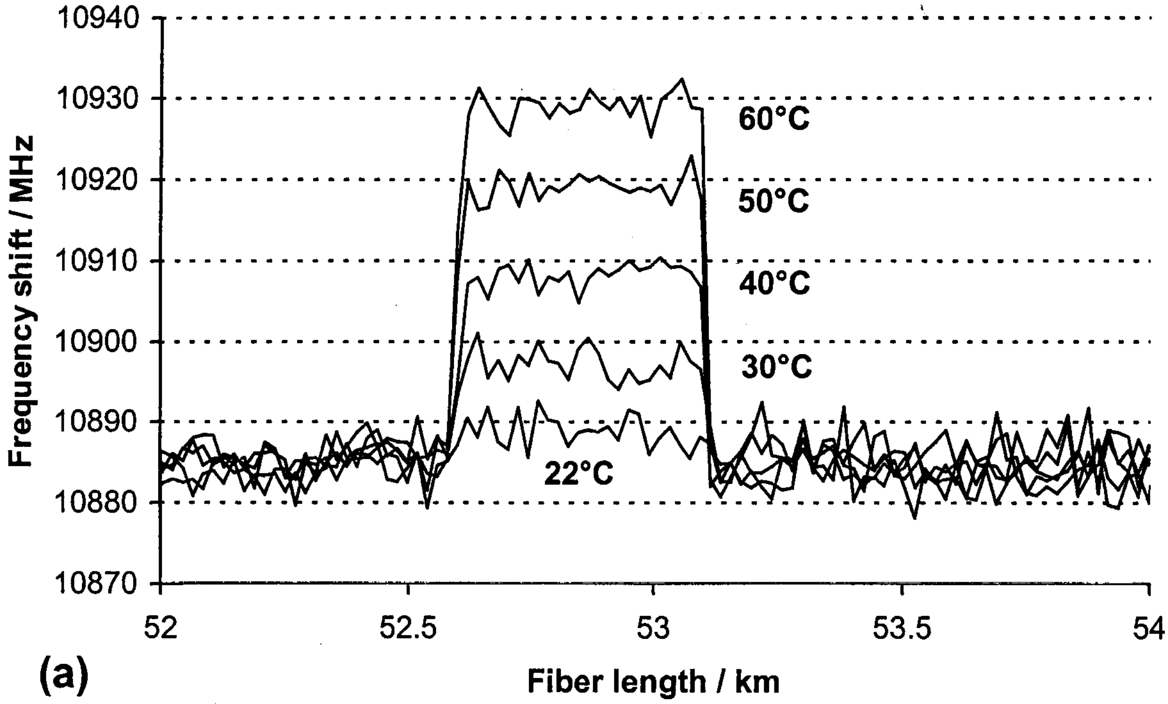
(a)



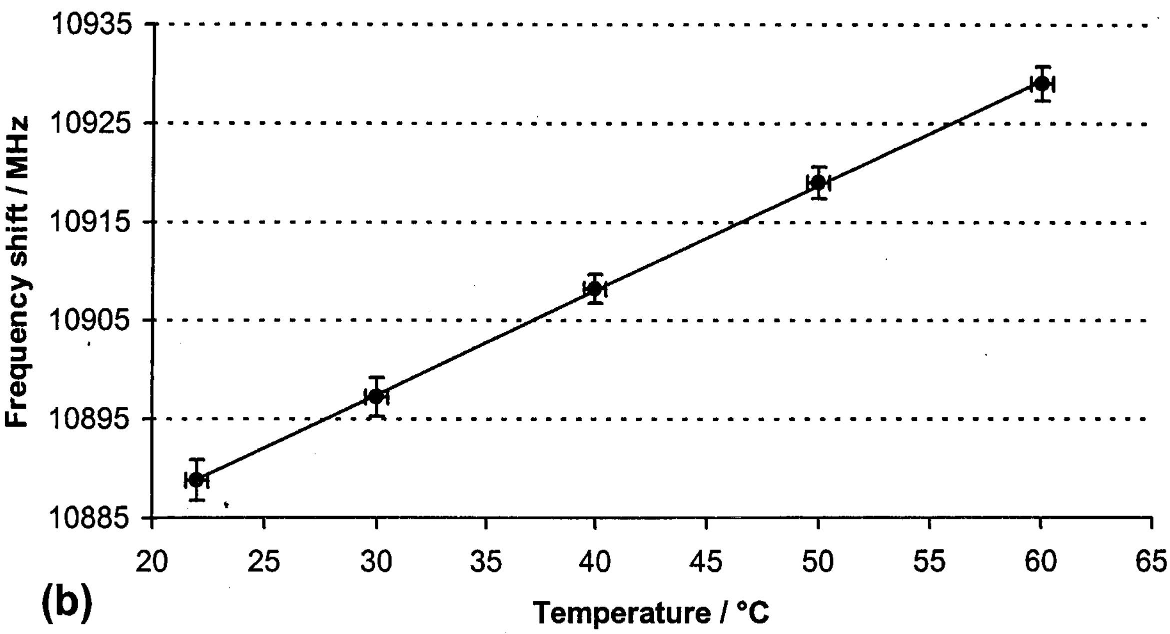
(b)

Figure 2, S.M.Maughan, Optics Letters

TOP



(a)



(b)

Figure 3, S.M.Maughan, Optics Letters