Multiplexed Sensing using Optical Low-Coherence Reflectometry

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A novel multiplexed optical sensor permitting absolute length measurement in remote reflective sensor arrays is proposed. Based on optical low-coherence reflectometry, this technique has been used to demonstrate length measurements to within 10 microns for 6 meter sensor cables situated 70 km from the receiver.

1. Introduction

Low coherence interferometry is an attractive technique for sensor measurements[1,2,3,4]. While it maintains the accuracy of conventional single-frequency (i.e. long coherence length) interferometry, it avoids many of the limitations and problems associated with long coherence length signals. One main advantage is that absolute length or time delay can be measured. This is in contrast to fixed-frequency coherent interferometry where only changes in delay can be measured. Also, due to the short coherence length of the sensing signal, undesirable time-varying interference from stray system reflections is eliminated. Another advantage is the ability to coherence multiplex[5] many sensors onto a single optical signal without requiring the use of relatively complex time or frequency multiplexing techniques. These coherence multiplexed schemes typically use separate receiving interferometers whose time delays are matched to the remote sensing interferometers[5]. The sensing interferometers are totally passive and the demultiplexed interference signals are insensitive to any phase or length changes in the connecting fiber leads.

In this paper, we propose and demonstrate a new low-coherence multiplexed sensing scheme which measures the absolute optical path lengths between reflectors spaced along a single sensing fiber. This method differs from previously demonstrated coherence multiplexed schemes[5] in that only one reference interferometer is needed and only a single fiber lead is required to supply both input and output signals. This is advantageous since it greatly reduces the complexity and cost for a coherence multiplexed sensor array.

The proposed sensing scheme will be useful for the remote measurement of temperature or strain. An important application could be deformation sensing in smart-skin structures[6]. By incorporating fiber-optic sensor arrays into structures such as bridges, building frames, dams and tunnels, smart structures can be realized for situations where material strains must be monitored throughout the lifetime of the structure.

2. Description

The proposed multiplexed sensing technique is illustrated in Figure 1. A low-coherence source is coupled into the fiber sensor array located at the end of a long fiber lead. A long fiber lead of length L, is used to demonstrate the lead insensitivity and measurement range possible with this approach. The reflectivities of the in-line reflectors are small (1% or less) to avoid depletion of the input probe signal. The fiber sensor lengths X_{ij} between adjacent reflectors can be of any value as long as the differences in their lengths are not larger than the scan range of the autocorrelator. The autocorrelator is scanned about a delay offset which approximately equals the time delay associated with the individual sensing fibers. In our experiment, the fiber sensor lengths were approximately 6 meters long and X_{ref} was set such that the difference between X_{ij} and X_{ref} was within the 40 cm scan range of the receiving autocorrelator. As the autocorrelator is scanned, interference signals occur whenever the path difference matches the distance between adjacent reflectors in the sensing array. Unwanted interference signals associated with non-adjacent reflectors lie outside the scan range and are not detected. The sensing fibers can be arbitrarily long since the desired interference signals from the sensor array are aliased into a relatively small scan range due to the matched offset length, X_{ref}, in the autocorrelator.

The width of each interference signal is approximately equal to the coherence length of the source, which is typically on the order of a few tens of microns. The location of the interference signals is a direct measurement of the absolute optical path length of each sensing fiber. The strength of these interference signals depend on the product of the reflectivities from adjacent reflection sites. Because the scan range is much larger than the width of the interference signals, the chance of signal overlap is small. If interference signals do overlap for a short time, they can be identified when they separate by keeping track of their amplitudes which in general are not equal. Although the interference signals are polarization dependent, complete nulling due to orthogonal polarization states is unlikely due to the wavelength dependence of the fiber birefringence and the wide spectral width of the source.

3. Experimental Results

The arrangement illustrated in figure 1 was experimentally demonstrated using an array of 7 sensing fibers. The sensing fibers were commercial telecommunication patchcords terminated with FC-PC connectors. Each fiber was approximately 6 meters long and coated with a 900 μm plastic buffer. The low-coherence signal was generated by a two-pass erbium doped fiber noise source[7]. This source generated 6 mW of optical power centered at a wavelength of 1.55 μm with a spectral width of about 25 nm. A 3 dB fused coupler was used to couple the low-coherence signal to the sensor array and the reflected signals to the autocorrelator.

A commercially available optical low-coherence reflectometer (HP 8504A Precision Reflectometer) performed the autocorrelation function. The scan range of the reflectometer is 40 cm (air distance). A 6 m patchcord was used in the reference arm. The test port was left unconnected resulting in a Fresnel reflection which was used to interfere with the delayed signal from the reference path. Since the reflectometer displays the square of the detected photocurrent, the amplitudes of the interference peaks are proportional to the product of the reflectivities from adjacent reflectors in the sensing array.

Figure 2 shows the reflection peaks corresponding to the seven sensing fibers located at the end of a 6 km spool of standard telecommunications fiber. All the sensing signals could be displayed in a 10 cm scan range of the autocorrelator. Because the patchcords had large variations in reflectivity (-10 to -40 dB), small pieces of cellophane were placed between connectors in the sensor array to provide a more consistent reflectivity. With higher quality connectors this would not be necessary. Each interference signal was more than 30 dB above the noise floor, demonstrating the excellent signal to noise ratio for this technique. The measured interference signals were not affected by chromatic dispersion or environmentally induced pathlength changes in the 6 km fiber lead connecting the sensors to the autocorrelator. Peak signal heights varied by less than 10 dB as the birefringence of the fiber leads were adjusted.

To investigate the applicability of this technique for very long lead lengths, the sensor array was placed at the end of a 70 km fiber length. Successful operation of this sensor is shown in figures 3 and 4. Figure 3 shows the shape (plotted on a linear scale) of one of the interference signals. Although the low-coherence sensing signal had to travel 140 km (to the sensor array and back again), the 3 dB width of 27 μm was the same as for the case when no fiber lead was used (i.e. L = 0). The small amount of broadening which appears as sidelobes on the interference signal is believed to be due to the polarization mode dispersion of the 70 km lead length. Although the integrated Rayleigh backscatter power dominated over the reflected sensor powers, the interferometric nature of the autocorrelation receiver allowed for good signal to noise of the sensor signals.

Figure 4 shows the ability to make accurate optical path length measurements on the sensing fibers. The sensor length shown in figure 3 was placed in a water bath so its temperature could be accurately controlled and measured. The optical path length change (referenced to air) of the 6 meter fiber cable is plotted in figure 4 as a function of temperature. The curves A and B show that the optical length change depends strongly on the mechanical history experienced by the fiber cable. Curve A was measured just after coiling the cable to a 3 inch diameter and heated for the first time. After the initial heating, which relieved the mechanical stress stored in the plastic buffer, the temperature was ramped again and curve B was obtained. The fractional optical path length change as a function of temperature varied from 2 to 3.8×10^{-5} C^{-1} which is slightly larger than the 10^{-5} C^{-1} value for pure silica. Since the length of the 6 meter cables could be measured to better than 10 μm (see figure 3), a temperature change of less than 0.1 C could be detected. To accurately measure absolute temperature, a fiber coating material with consistent performance is required.

4. Discussion and Summary

Although reflectivities from standard FC/PC connectors were used to realize the sensor array, a more practical solution might consist of using recently developed intra-core reflective fiber gratings. By forming these gratings during the fiber drawing process[8], accurate spacing and reflectivity control should be possible. Also, by using gratings centered at different wavelengths, identification of individual sensors can be accomplished without the need to rely on the amplitudes of the interference signals. Although equal fiber lengths were used in the sensor array, this constraint can be lifted if a recirculating delay is used in one of the autocorrelator arms. This concept has been used to extend the measurement scan range in optical low-coherence reflectometry[9].

A low-coherence technique for performing multiplexed measurements on a fiber sensor array has been proposed and demonstrated. A practical implementation of this technique is presented which makes use of a commercially available optical low-coherence reflectometer and fiber cables. The sensor array is completely passive and absolute length measurements can be obtained for each sensing fiber. At the end of a 70 km fiber lead, 6 meter long sensing fibers were measured with an absolute accuracy of 10 μm. This multiplexed sensor scheme should be useful in remote measurement applications such as fiber-optic smart structure monitoring[6].

5. References

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Figure Captions

1. Arrangement for the remote measurement of fiber lengths in a sensor array.

2. Experimental measurement of the length of seven sensing fibers, each 6 meters long, multiplexed into a 10 cm scan range of the autocorrelator. The remote sensing array was located at the end of a 6 km fiber. The numbers above each peak indicate the two reflection sites contributing to the interference signal.

3. Response from an individual sensor located at the end of a 70 km fiber lead. Fiber lengths can be measured to an accuracy of 10 μm.

4. Temperature dependence of a 6 meter fiber cable measured at the end of a 70 km fiber lead. Curves A and B illustrate that the mechanical history of the plastic fiber jacket can affect the optical path length changes.

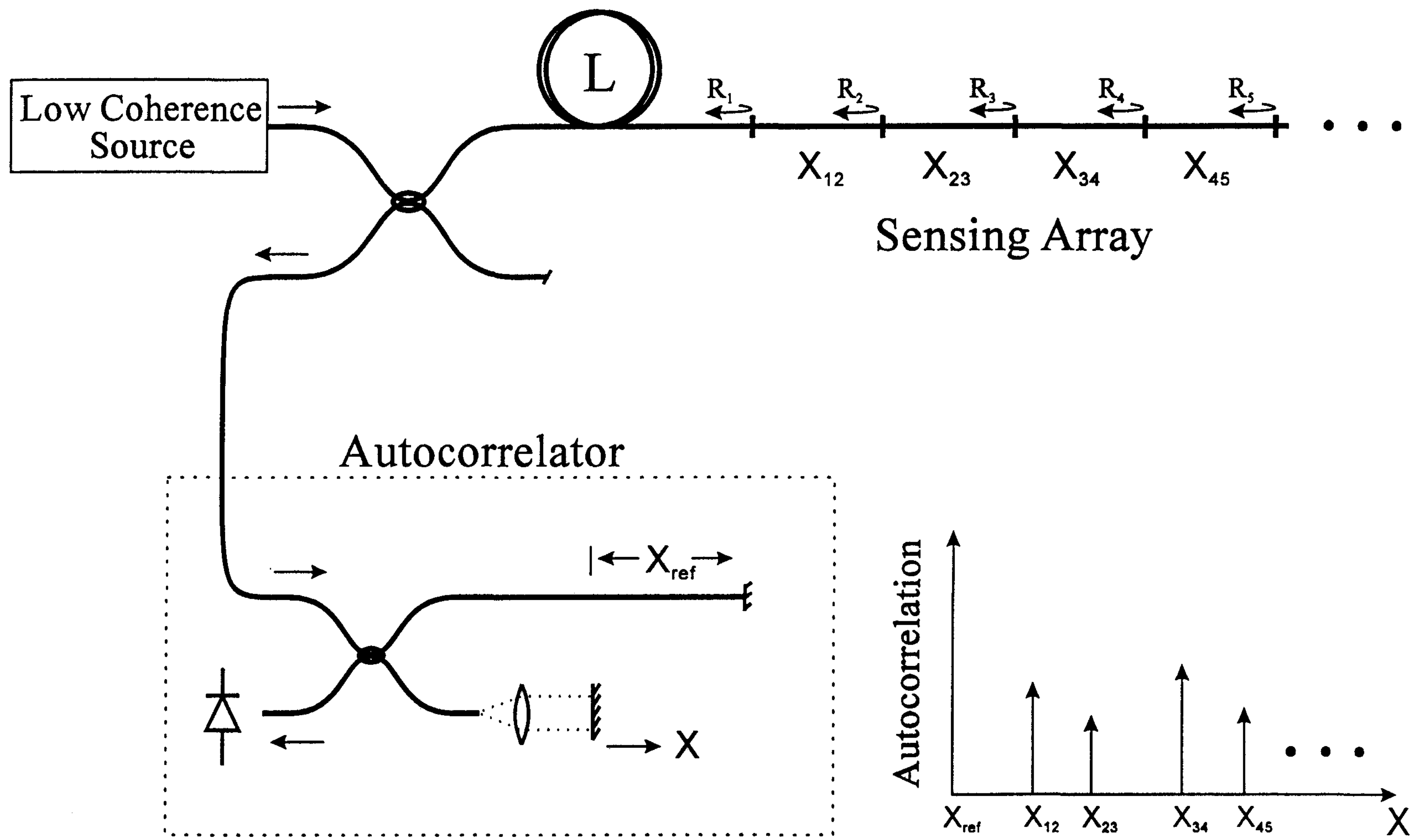

Low Coherence Source
L
R1
R2
R3
R4
R5
X12
X23
X34
X45
Sensing Array
Autocorrelator
Xref
X
Autocorrelation
Xref
X12
X23
X34
X45
X

Figure 1

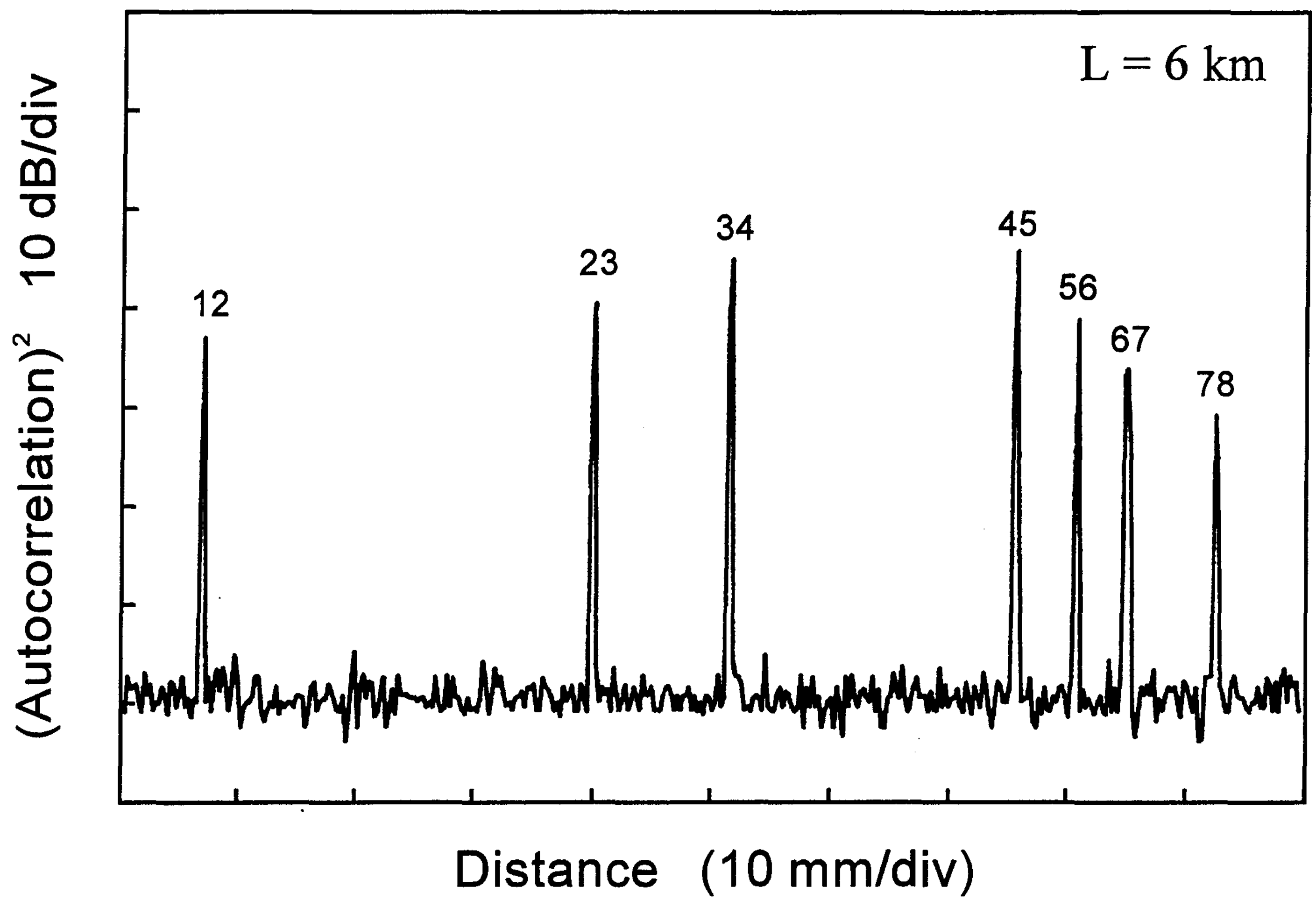

L = 6 km
12
23
34
45
56
67
78
(Autocorrelation)^2 10 dB/div
Distance (10 mm/div)

Figure 2

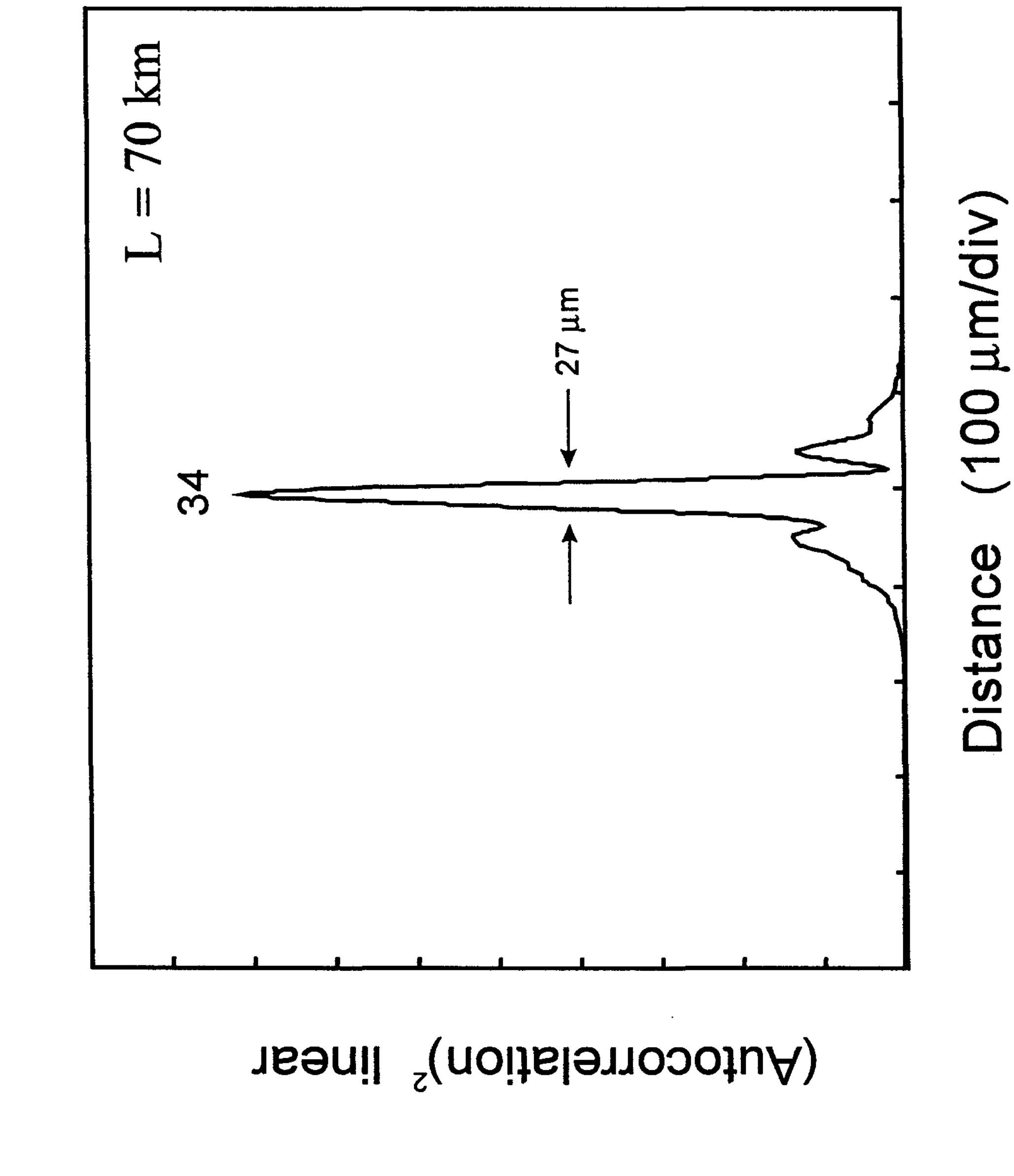
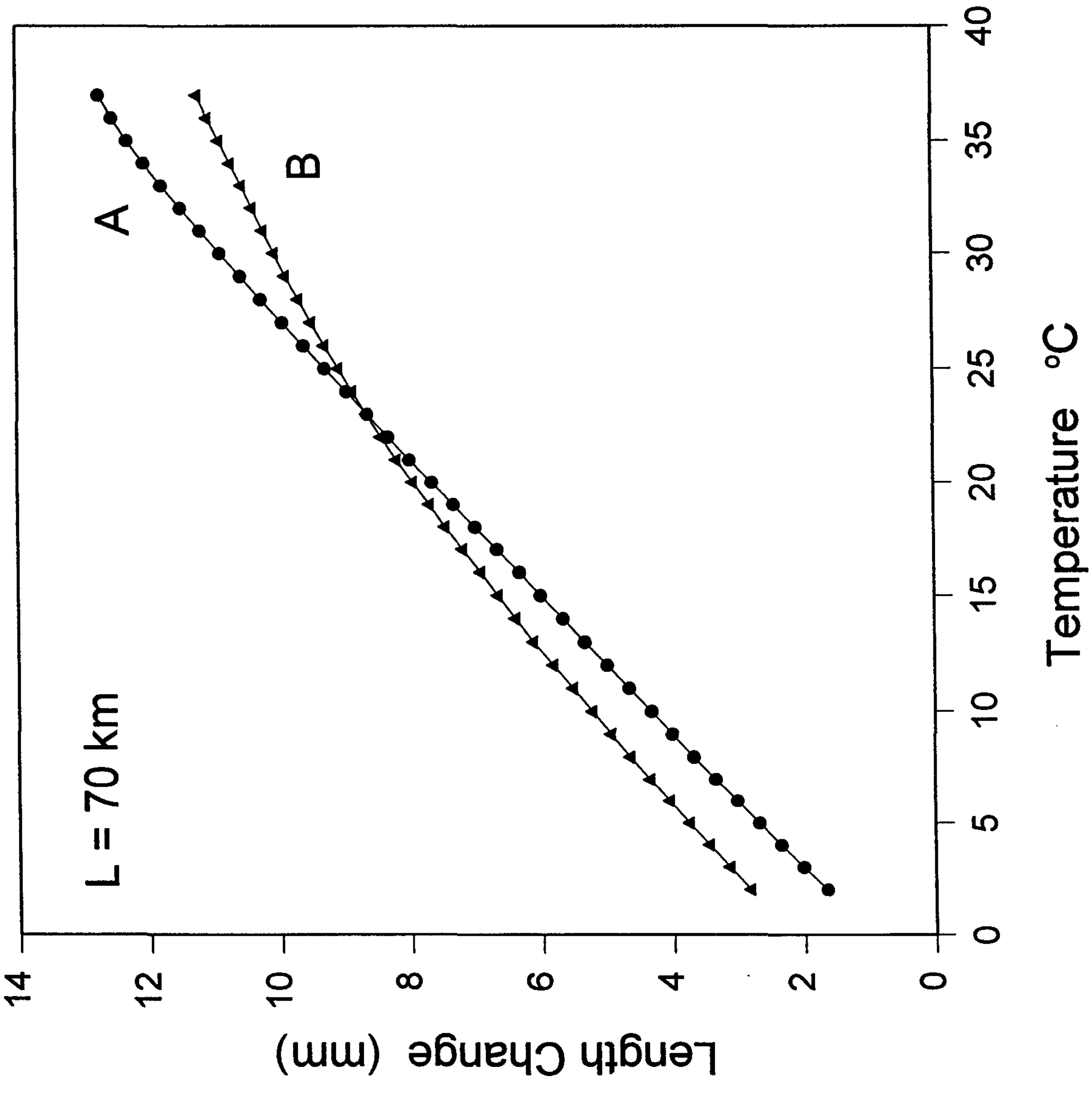


Figure 3



L = 70 km
A
B
Length Change (mm)
Temperature °C
0
2
4
6
8
10
12
14
0
5
10
15
20
25
30
35
40

Figure 4