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Polarimetric Er^{3+}-Doped Fiber DFB Laser Sensor for Differential Pressure and Force Measurements

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We propose and demonstrate a polarimetric Er^{3+}-doped fiber DFB laser sensor where a transversely applied force along the fiber laser induces a birefringence giving rise to a change in the beat-frequency between the two orthogonally-polarized laser modes. We measure a sensitivity of approximately 9.6GHz/(N/mm), a wide dynamic range with stable two-mode operation for frequency separations up to 50GHz, and very high sensor resolution owing to the narrow beat frequency bandwidth of <10kHz. The temperature sensitivity is primarily dominated by the temperature dependence of the inherent birefringence, which was measured to be -130kHz/°C. The sensor allows independent pressure/force and temperature measurements.

Fiber Bragg grating (FBG) sensors have been attracting a lot of interest over the last few years owing to their compactness, multiplexing capabilities, and wavelength-encoded nature. Active (laser) FBG sensors have the advantage of providing high signal-to-noise ratios and potentially very high resolution. Recently, a single-mode polarimetric distributed Bragg-reflector (DBR) fiber-laser strain sensor was demonstrated [1], enabling very simple and elegant interrogation through measurement of the RF beat frequency between the two orthogonal polarization of the laser sensor, rather than through more conventional (and complicated) absolute wavelength interrogation.

In this paper we propose and demonstrate a polarimetric fiber laser sensor based on a dual-polarization phase-shifted fiber DFB laser [2, 3], which has the advantage of requiring only one single FBG, and through strong side-mode-suppression eliminating the problem of detrimental mode-hopping, which can occur in a DBR fiber laser if the two FBGs and the fiber in-between are exposed to different temperature or strain. Since the two polarization modes of a fiber DFB laser have the same spatial periodicity, no spatial holeburning will occur. Hence, the two-mode operation must be caused by polarization holeburning (PHB) [4]. The PHB effect is strongest when the two modes are orthogonal and linearly polarized, as will normally be the case in a fiber DFB laser, and will increase with increasing gain compression, which in a laser can be defined as difference between the maximum available gain and the (threshold) laser gain.

The wavelength separation between the two orthogonal laser modes of a (phase-shifted) fiber DFB laser is (differently from a fiber DBR laser [1]) simply given by:

$$\Delta\lambda = 2B\Lambda = \lambda_{x,y} \frac{B}{n_{x,y}} \tag{1}$$

where Λ is the FBG pitch, $\lambda_{x,y} = 2n_{x,y}\Lambda$ is the x- and y-polarized laser wavelength, $B = n_x - n_y$, where n_x and n_y are the refractive indices along the x- and y-eigenaxis of the fiber.

By placing the DFB fiber laser sensor between two parallel plates we measure the shift in beat frequency as a function of an applied transverse force, which introduces a birefringence B_f in the fiber given by [5]:

$$B_f = \frac{4Cf}{\pi r} \tag{2}$$

where $C = n_0^3(p_{12}-p_{11})(1+v_p)/(2E)$ is the (relative) opto-elastic constant [5], f is the force per unit length [N/mm], and r is the fiber radius. n_0 is the average fiber refractive index, E and v_p is the Modulus of Elasticity and Poissons ratio for the fiber, respectively, and p_{12} and p_{11} are the photoelastic coefficients of silica. The value of C varies in the literature, but with typical values for fused silica [5], $p_{12} = 0.27$, $p_{11} = 0.12$, $v_p = 0.17$, $E = 7.6*10^4 N/mm^2$, and $n_0 = 1.444$ (at 1.55μm), the above formula yields $C = 3.5*10^{-6}$ mm^2/N. Using this value of C together with r = 62.5μm and $\lambda = 1.55\mu m$ in (1) and (2), the shift in beat frequency with applied transverse force, $\delta(\Delta v)/f \approx 9.6$GHz/(N/mm).

From (1) we find that the shift in beat frequency with fiber strain $\delta(\Delta v)/\varepsilon = \Delta v$, providing

B does not change with strain. Recently an Er^{3+}-doped fiber DFB lasers with $\Delta\nu$ = 400MHz was demonstrated [6], in which case $\delta(\Delta\nu)/\varepsilon$ = 0.4MHz/mstrain. In comparison the strain sensitivity of the DBR laser in [1] was ≈ 4.1MHz/mstrain, i.e. one order of magnitude higher, since the two orthogonal modes belonged to adjacent longitudinal orders.

The temperature sensitivity of the DFB fiber laser sensor beat frequency can from (1) be obtained as:

$$\frac{\delta(\Delta\nu)}{\delta T}=\left(\frac{1}{B}\frac{\delta B}{\delta T}+\alpha\right)\Delta\nu \qquad (3)$$

where α is the thermal expansion coefficient of the fiber ($\approx 0.55\cdot10^{-6}\,{}^{\circ}C^{-1}$ for silica). When the fiber is placed between two plates (much thicker than the fibre) α can normally be replaced by α_{pl}, where α_{pl} is the expansion coefficient of the plate material. The temperature dependence of the fiber birefringence is more complicated, since the birefringence is the (vector) sum of three contributions; (i) the inherent (stress) birefringence, (ii) the UV induced birefringence, and (iii) the transverse-force-induced birefringence (B_f in (2)), which will all have different temperature dependencies. We have measured the temperature dependence of the fiber birefringence B_0 without an applied force (i.e. contribution (i) + (ii)), and will discuss this dependence and the expected temperature dependence of B_f (iii) later.

An important feature of the proposed sensor is that the transverse force and the temperature can be measured independently by measuring both the wavelength separation $\Delta\lambda$ (through the beat frequency) and the absolute value of one (or both) of the two laser wavelengths $\lambda_{x,y}$, alternatively the average wavelength, since B and $n_{x,y}$ have different temperature dependence, and also different transverse-force dependence.

We tested 3 Er^{3+}-doped fiber DFB lasers which were similar to the laser reported in [6] (using the same fiber), two 10cm long lasers with wavelengths 1532 and 1549nm, and one 3.5cm long laser with a wavelength 1532nm. The experimental setup is shown in Fig. 1. All lasers were pumped by a pigtailed 980nm diode laser (Lasertron) through a WDM coupler, and the returned laser output was going through an optical isolator, a fiber polarization controller and a pigtailed rotatable linear polarizer (JDS Fitel), before the two wavelengths were mixed in an AC-coupled 2GHz-bandwidth receiver (InGaAs PIN diode with a transimpedance amplifier). The output was analyzed by an RF spectrum analyzer. The stripped fiber DFB laser was placed between two 10x5x125mm (WxHxL) glass plates with tape in a specially made force rig, as illustrated in Fig. 1. The glass plates were glued to 10x50x120mm steel bars, which were stiff enough to maintain a constant force along the fiber. The applied force was measured by two symmetrically positioned load cells 63mm apart. The fiber could be rotated at both fixing points. During the experiments we ensured that the fiber lasers were not twisted. We measured the beat frequency as a function of the total force applied to the fiber for various orientations θ of the fiber eigenaxis y (defined by the inherent+UV induced birefringence) relative to the ψ-axis (see Fig. 1), where ψ is the direction of the applied force. The results of these measurements are shown in Fig. 2 for the 3.5cm long DFB fiber laser having $\theta \approx 0°$ and $90°$ ($\pm 5°$) together with corresponding theoretical curves. The unloaded laser had a beat frequency $\Delta\nu_0 \approx 441$MHz, which corresponds to a birefringence of $B_0 = n_0\, \Delta\nu_0/\nu_0 \approx 3.3 \cdot 10^{-6}$, where ν_0 is the average laser frequency. From Fig. 2 we observe that the beat frequency increases most rapidly for $\theta = 0°$, in which case the y-eigen-axis of the fiber is approximately aligned with the applied force (ψ-axis), and $B = B_0 + B_f$. When $\theta = 90°$, the beat frequency first decreases with increasing applied force, then starts to increase with the same slope as for $\theta = 0°$. This is expected since for $\theta = 90°$ $B = |B_0 - B_f|$ [5]. Note that we could not measure frequencies below ~180MHz owing to the design of the receiver. The fit to the theoretical curves is excellent, with a measured sensitivity S very close to the calculated value of 9.6GHz/(N/mm) (with $C = 3.5 * 10^{-6}$mm^2/N). The bandwidth $\Delta\nu_B$ of the electrical beat signal of the 1549nm fiber DFB laser was measured to be <10kHz with a scan-time of 1s. Hence, the resolution of the sensor $\equiv \Delta\nu_B/S < 1 \cdot 10^{-6}$N/mm, which for the width of the glass plates W = 10mm, corresponds to a (differential) pressure resolution of <0.1Pa with a sensitivity of 96kHz/Pa. This implies that the sensor could possibly be used as an acoustic sensor.

Fig. 3 shows the optical spectrum of the 3.5cm long DFB laser with increasing applied transverse force, as measured (without polarizer) with a tunable, polarisation insensitive fiber Fabry-Perot filter (Micron Optics, Inc.) having a FSR of 279GHz and a finesse of 93. The laser operated robustly at two orthogonal modes, with some variations in the relative amplitude, for uniformly applied forces up to at least 7N/mm (limited by the dynamic range of the load cells), with a corresponding measured frequency separation of

44GHz. Note that most of the frequency shift (change in refractive index) occurs for the mode polarized normally to applied force, the orthogonal mode shifting only slightly in frequency with increasing force. It is possible that such a laser could be employed as a dual-frequency source with tunable (and stable) frequency separation.

The 10cm-long DFB fiber lasers had similar sensitivity, but the beat was much more sensitive to gradients in the applied force than the 3.5cm-long laser, as expected with a longer length. The 3.5cm laser produced a robust beat signal even with a strongly asymmetrically applied force. For example, with a measured force of 42N at one load cell and zero measured force at the other, corresponding to a force gradient of 0.67N/mm, a stable beat occurred at about 3.5GHz. Note that both 1532nm lasers suffered from self-pulsation (the 3.5cm laser at around 150kHz), with resulting side-bands in the beat signals. The 10cm-long laser operating at 1549nm did not self-pulsate, but the beat was more unstable than for the 10cm 1532nm long laser, possibly owing to a lower gain compression at 1549nm than at 1532nm, and hence a weaker PHB effect [4]. We did not observe any effects of changing the polarization state of the pump.

We measured simultaneously the change with temperature of the beat frequency and the average laser frequency (without an applied force) of the 1549nm DFB fiber laser by placing the laser inside a temperature test chamber. Changes in average laser frequency was measured with the tunable fiber Fabry-Perot filter. The change in average frequency was measured to be ≈0.94GHz/°C (7.6pm/°C), while the change in beat frequency

$\delta(\Delta\nu)/\delta T$ was only $\approx$-0.13MHz/°C (see Fig. 4). This implies that (with W = 10mm) a temperature change of 1°C is equivalent to a change in differential pressure of only $\approx$1.4Pa. The laser was tuned in temperature from -10 to 50°C, corresponding to a change in average wavelength of $\approx$0.5nm, without any mode-hopping. The negative change in beat frequency with increasing temperature is believed to be due to stress relaxation in the fiber. This agrees with the fact that fiber stress birefringence is proportional to $(\alpha_{cl}-\alpha_{co})(T_a-T_g)$, where α_{cl} and α_{co} are the thermal expansion coefficient of the cladding and the core (normally $\alpha_{co} > \alpha_{cl}$), and T_a-T_g is the difference between the ambient temperature and the softening temperature of the glass [5]. Referring back to equation (3), $\delta(\Delta\nu)/\delta T \approx -0.13$MHz/°C corresponds to $(1/B_0)\ \delta B_0/\delta T \approx -0.3 \cdot 10^{-3}{}^\circ C^{-1}$, which is much bigger than the (positive) second term ($\sim 10^{-6}{}^\circ C^{-1}$) arising from thermal expansion. The temperature dependence of B_f in (2) is not known, but we assume (with careful sensor design) that this arises from the temperature dependence of the n_0^3-term in C, in which case $(1/B_f)\delta B_f/\delta T = 3\zeta$, where $\zeta \approx 8.3 \cdot 10^{-6}{}^\circ C^{-1}$ is the thermo-optic coefficient of silica. The beat frequency temperature dependence will then be dominated by the $\delta B_0/\delta T$-contribution for small values of B_f. However, when B_f increases, $(1/B)\delta B/\delta T$ approaches zero when B_f approaches $12B_0$. Hence, we expect the sensor to be temperature independent around some value of B_f.

In conclusion, we have demonstrated a simple, robust, differential pressure/force sensor, based on a dual-polarization-mode DFB fiber laser, with a very high sensitivity and wide dynamic range. The temperature sensitivity is probably low enough to eliminate the need for temperature compensation, however, the sensor enables independent measurements of both pressure/force and temperature.

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Figure captions:

Fig. 1 Experimental configuration

Fig. 2 Measured electrical beat frequency as a function of applied transverse force along the two fiber polarization eigenaxises ($\theta = 0°$ and $90°$) of a 3.5cm long Er^{3+}-doped fiber DFB laser. The solid lines are theoretical curves.

Fig. 3 Optical spectrum of 3.5cm fiber DFB laser with increasing transverse force, as measured with a fiber Fabry-Perot filter with a 3dB-bandwidth of 3GHz. The frequency is shown on a relative scale.

Fig. 4 Simultaneously measured electrical polarization beat frequency and change in average laser frequency of a (10cm) fiber DFB laser as a function of temperature (without an applied transverse force).

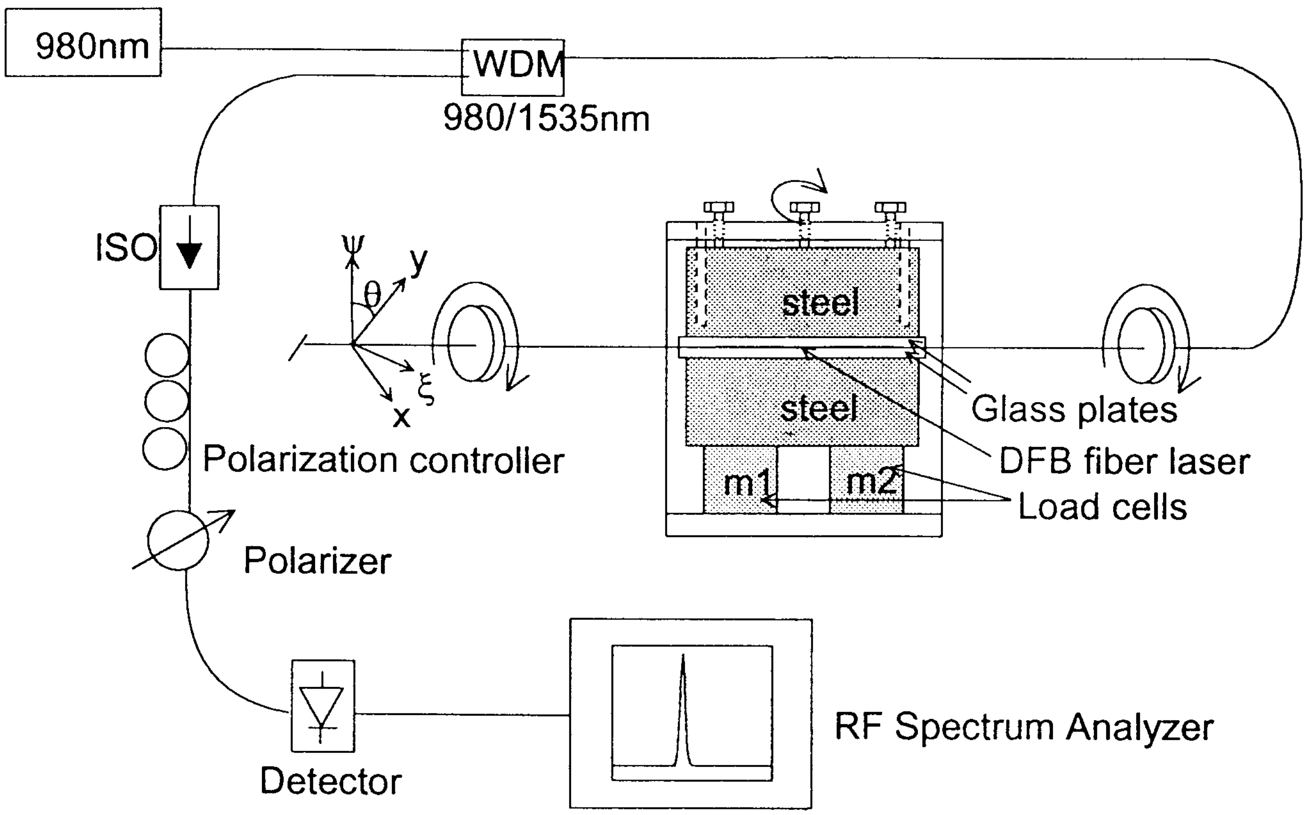
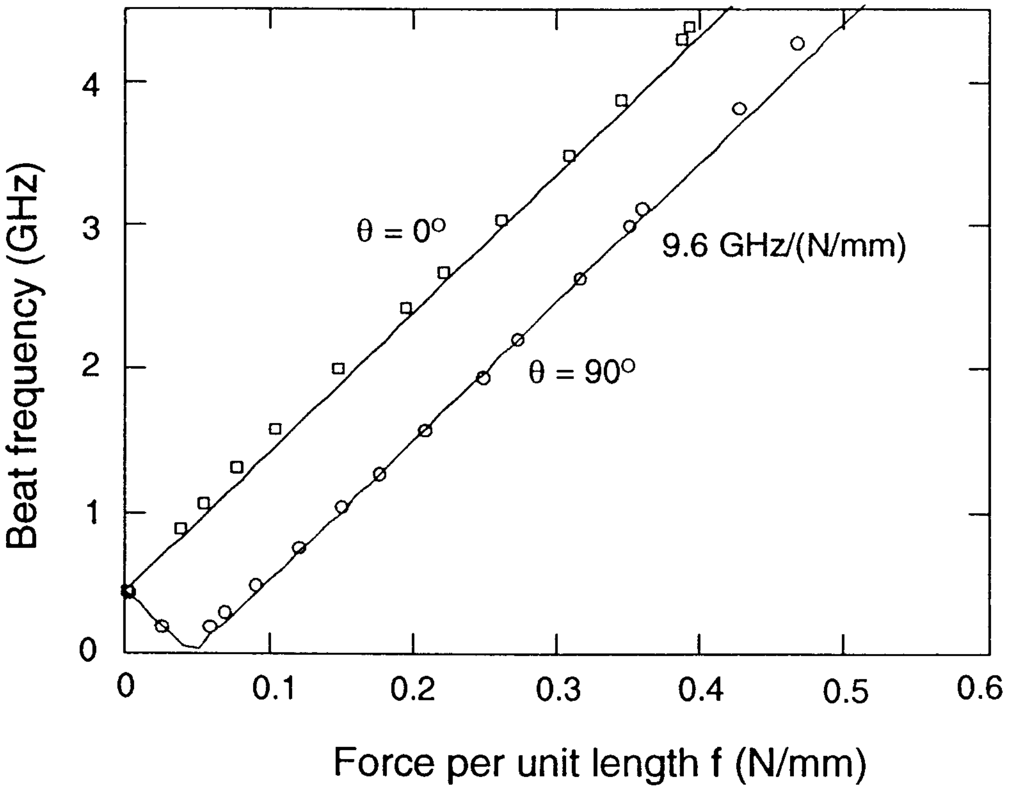

980nm
WDM
980/1535nm
ISO
ψ
y
θ
ξ
x
steel
steel
Glass plates
DFB fiber laser
m1
m2
Load cells
Polarization controller
Polarizer
Detector
RF Spectrum Analyzer

Fig. 1



Beat frequency (GHz)
0
1
2
3
4
0
0.1
0.2
0.3
0.4
0.5
0.6
Force per unit length f (N/mm)
θ = 0°
θ = 90°
9.6 GHz/(N/mm)

Fig. 2

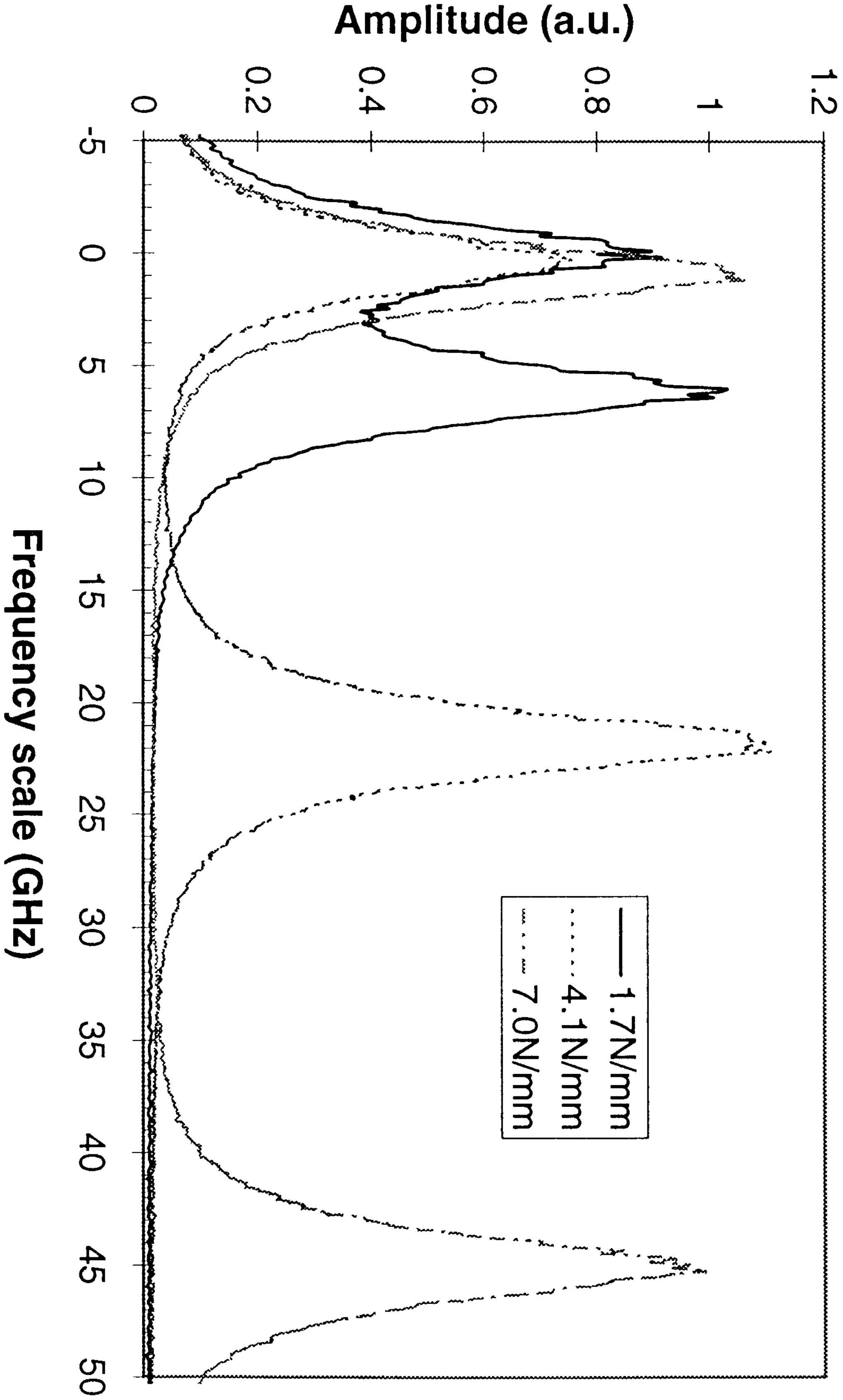

Amplitude (a.u.)
0
0.2
0.4
0.6
0.8
1
1.2
-5
0
5
10
15
20
25
30
35
40
45
50
Frequency scale (GHz)
1.7N/mm
4.1N/mm
7.0N/mm

Fig. 3

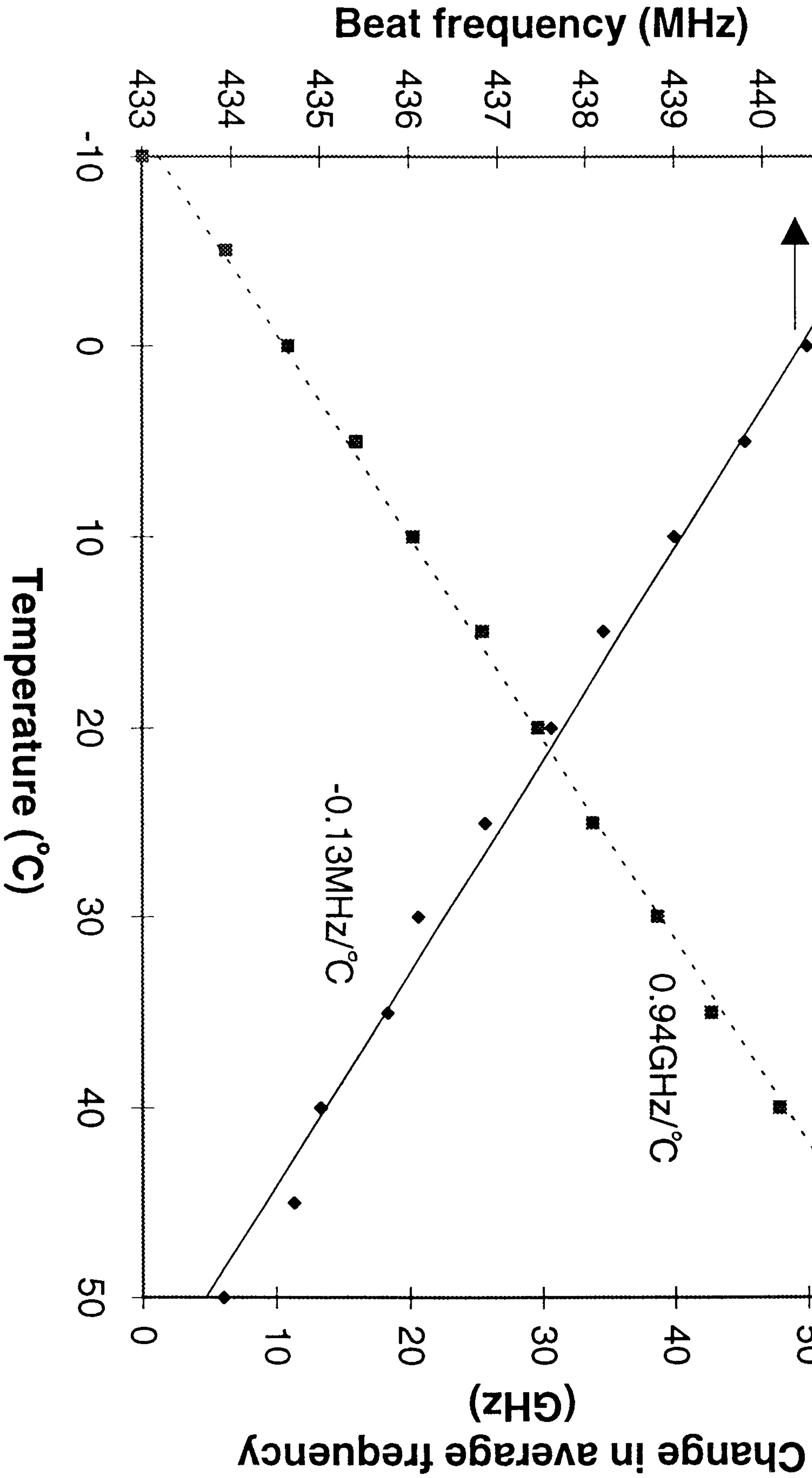

Beat frequency (MHz)
433
434
435
436
437
438
439
440
441
442
-10
0
10
20
30
40
50
Temperature (°C)
-0.13MHz/°C
0.94GHz/°C
0
10
20
30
40
50
60
Change in average frequency (GHz)

Fig. 4