

Fabrication of waveguide-based vibration sensors by femtosecond laser micromachining



**Masanao Kamata¹, Rafael R. Gattass², Loren R. Cerami²,
Eric Mazur² and Minoru Obara¹**

**Keio University, Yokohama (Japan)¹
Harvard University, Cambridge MA (USA)²**



Rafael R. Gattass



Loren R. Cerami



Eric Mazur



Minoru Obara

and also...

at Keio:

Prof. Toshiaki Makabe

at Harvard:

Dr. Alex Heisterkamp (now at LZH)

Dr. James Carey

Dr. Tommaso Balladacchini

Iva Maxwell

Geoff Svacha

Tina Shih

Financial supports:

- Japan Society for Promoting Science
- 21st century Center of Excellence in Keio for Optical and Electronic Device Technology for Access Network from the MEXT Japan.

contents

introduction

waveguide wiring

vibration sensor fabrication

vibration measurement

contents

introduction

waveguide wiring

vibration sensor fabrication

vibration measurement

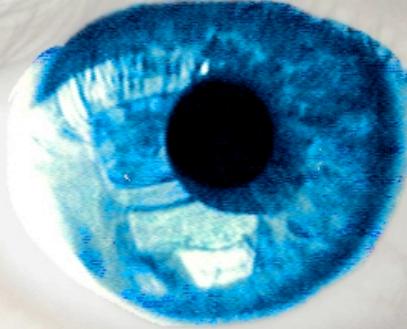
Structure health monitoring



technique to monitor and assess health of structures before catastrophic damage occurs



Structure health monitoring

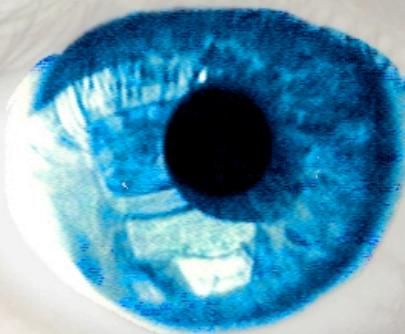


technique to monitor and access health of structures before catastrophic damage occurs

- **objectives**
buildings, vehicles, machines
- **physical quantities**
vibration, acceleration and displacement
- **methods**
electrical, optical



Optical sensing



- non electrical operation
- immunity from electromagnetic interferences
- small size and broad bandwidth



Fiber Bragg grating sensors

- **sensitive both to strain and temperature**
- **need additional equipments to measure vibration and acceleration**
- **expensive (also due to expensive masks)**

contents

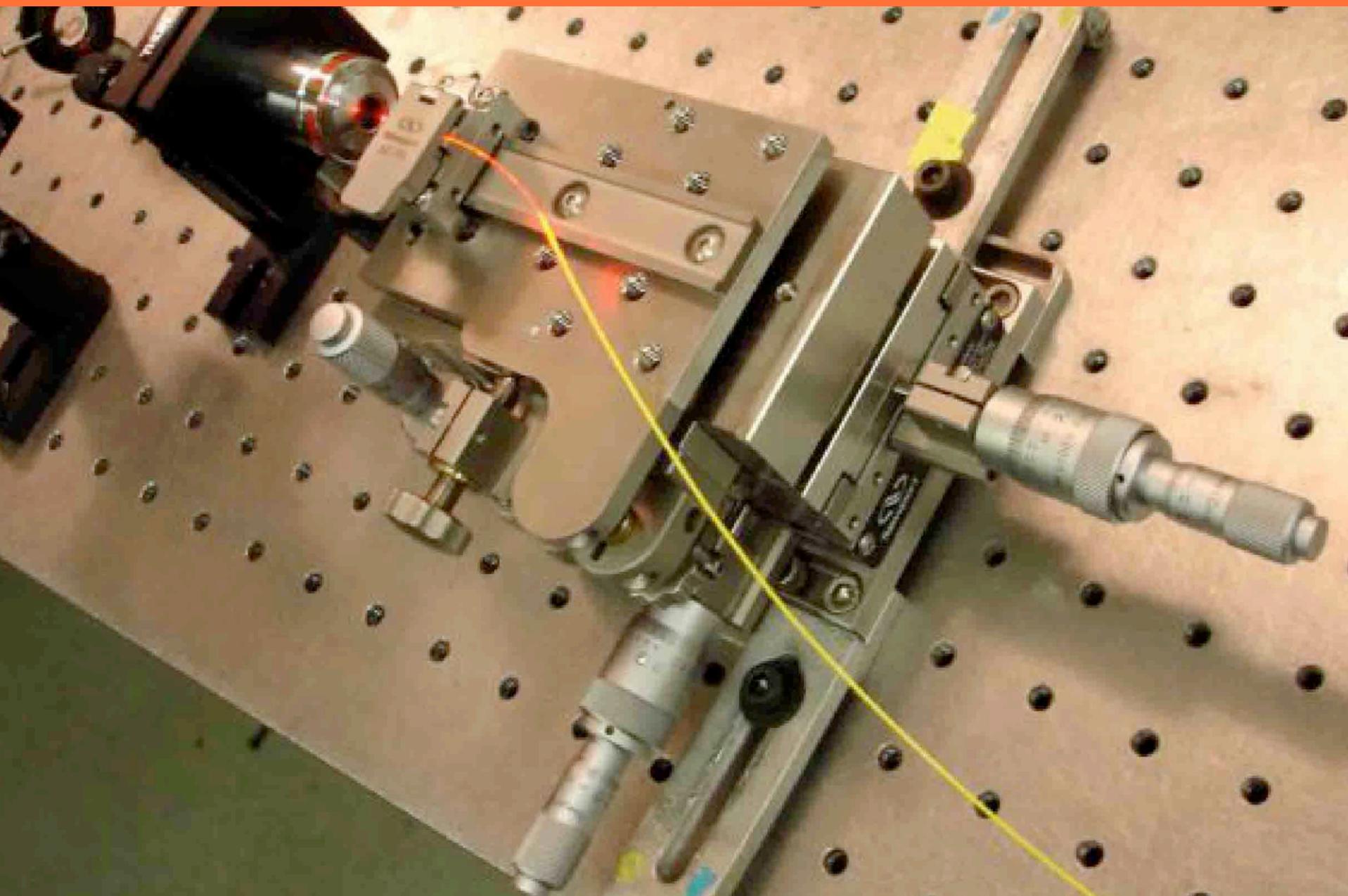
introduction

waveguide wiring

vibration sensor fabrication

vibration measurement

Coupling light to waveguide



Coupling light to waveguide

- core diameter : ~10 µm
(for single mode waveguides)
- accuracy of alignments < 1 µm
- use of precise 3-dimensional stages

Coupling light to waveguide

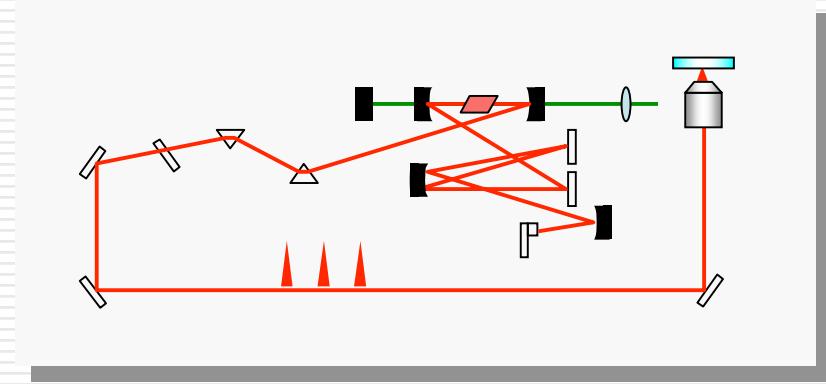
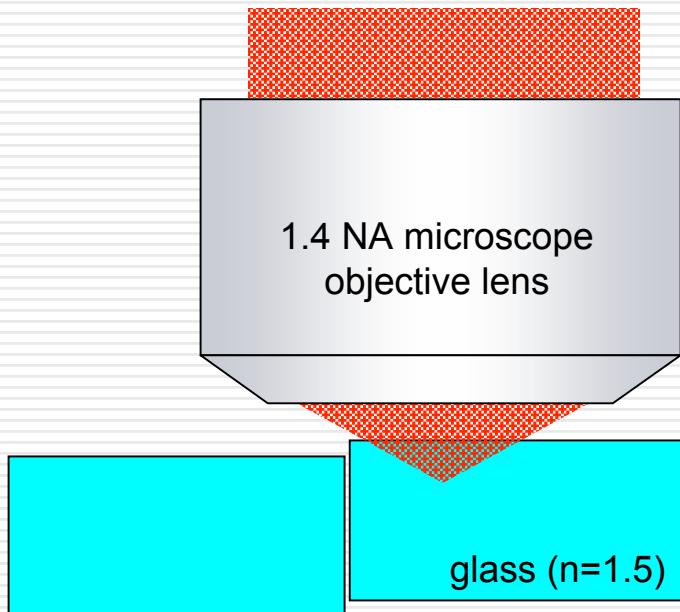
- core diameter : $\sim 10 \text{ } \mu\text{m}$
(for single mode waveguides)
- accuracy of alignments $< 1 \text{ } \mu\text{m}$
- use of precise 3-dimensional stages

waveguide-waveguide coupling:
active or passive alignments

needs cost and time!

Waveguide wiring by use of femtosecond lasers

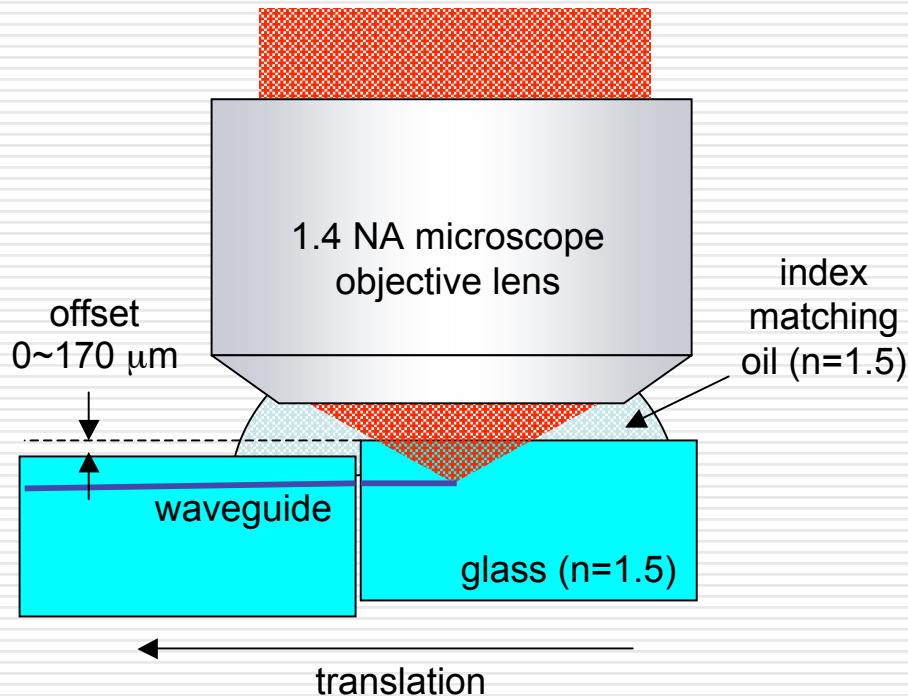
femtosecond laser pulses coming from
a long cavity Ti:Sapphire laser
10 nJ, 55 fs, 25 MHz, 800 nm*



a long cavity Ti:Sapphire laser

Waveguide wiring by use of femtosecond lasers

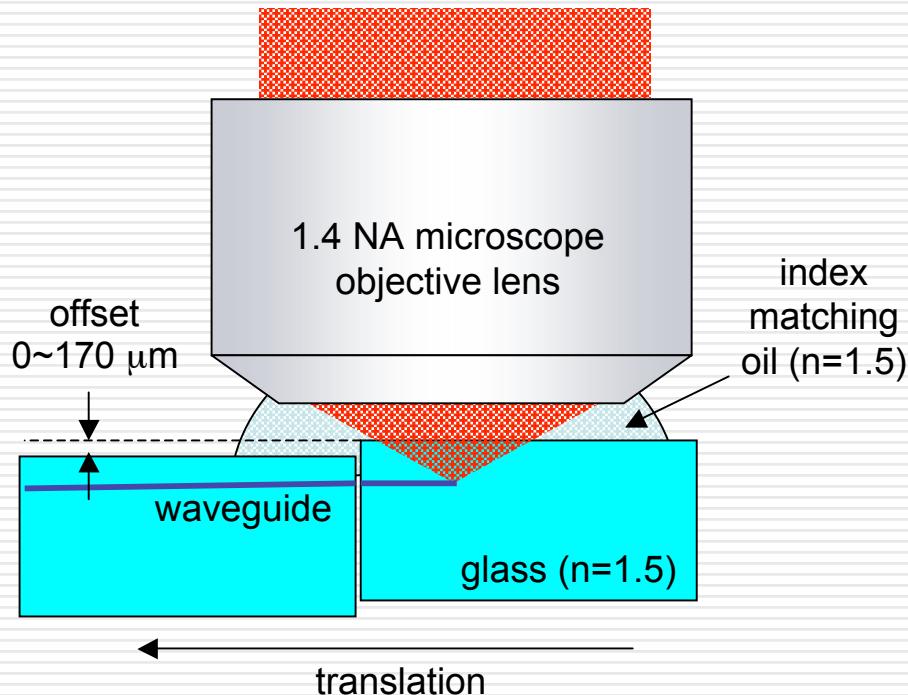
femtosecond laser pulses coming from
a long cavity Ti:Sapphire laser
10 nJ, 55 fs, 25 MHz, 800 nm*



- focal depth compensation by use of an index matching oil

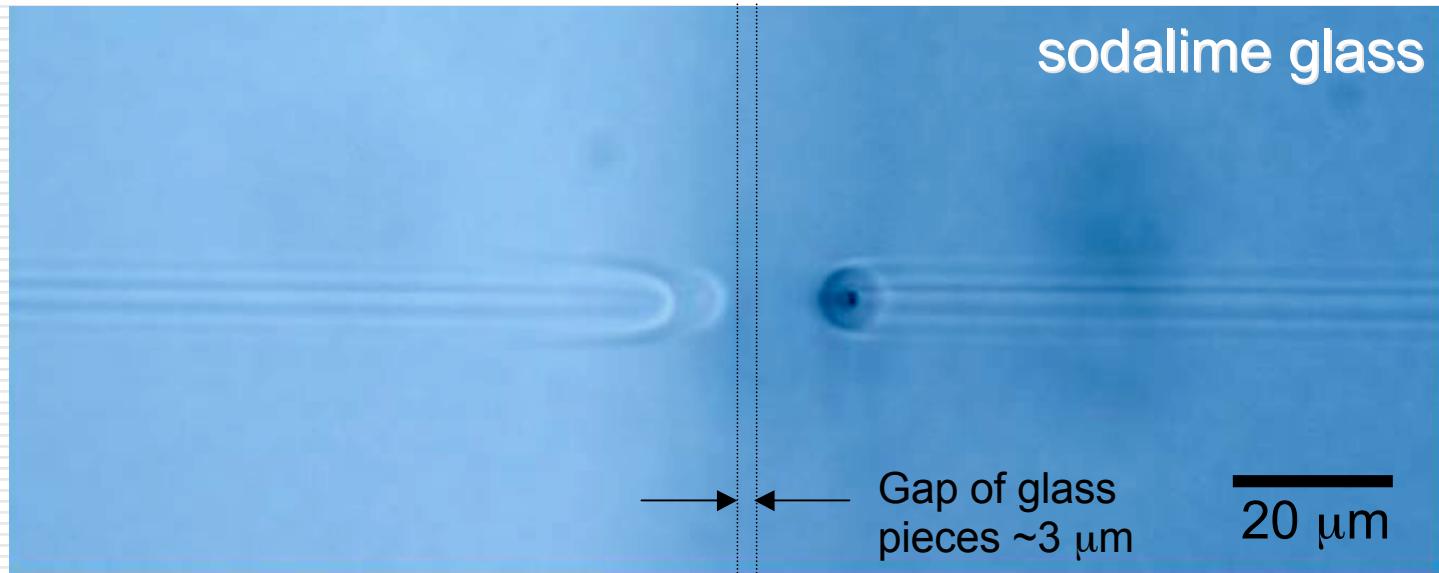
Waveguide wiring by use of femtosecond lasers

femtosecond laser pulses coming from
a long cavity Ti:Sapphire laser
10 nJ, 55 fs, 25 MHz, 800 nm*



- focal depth compensation by use of an index matching oil
- polishing and assembling prior to waveguides writing
- no post treatment
- reduction of accuracy of glass assembling process

Microscope picture of wired waveguides



Microscope picture of wired waveguides

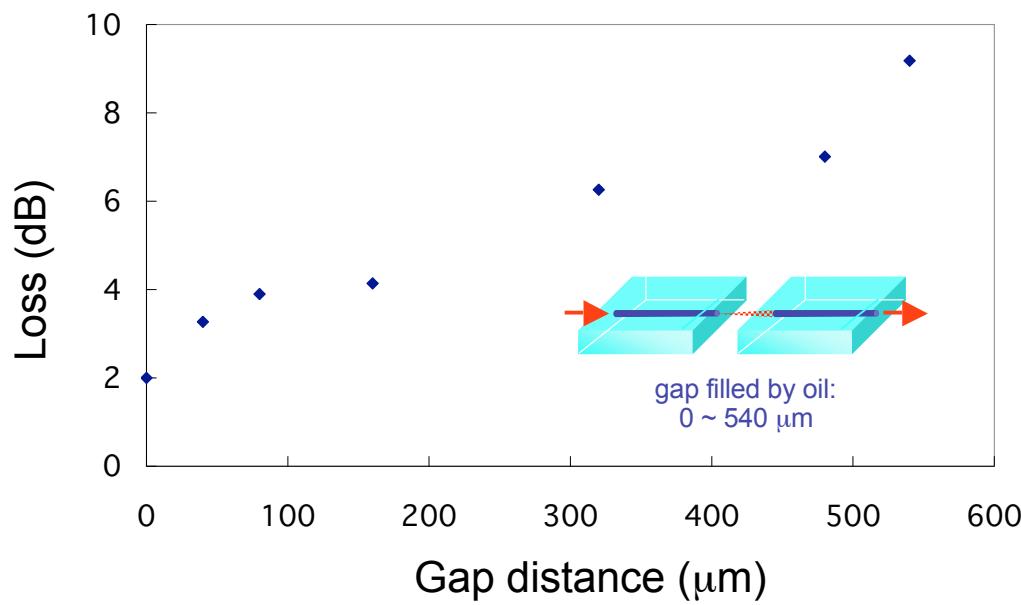
connection loss below 2.0 dB at 632.8 nm

“optically” wired

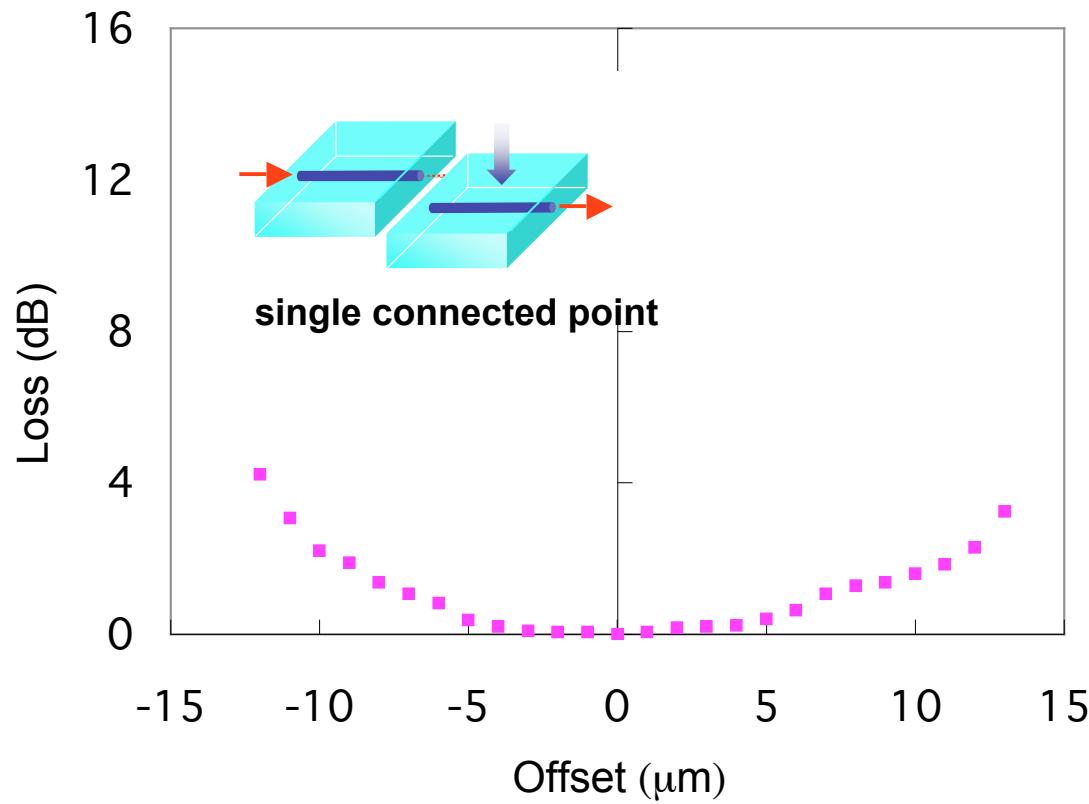


separation loss and lateral offset loss?

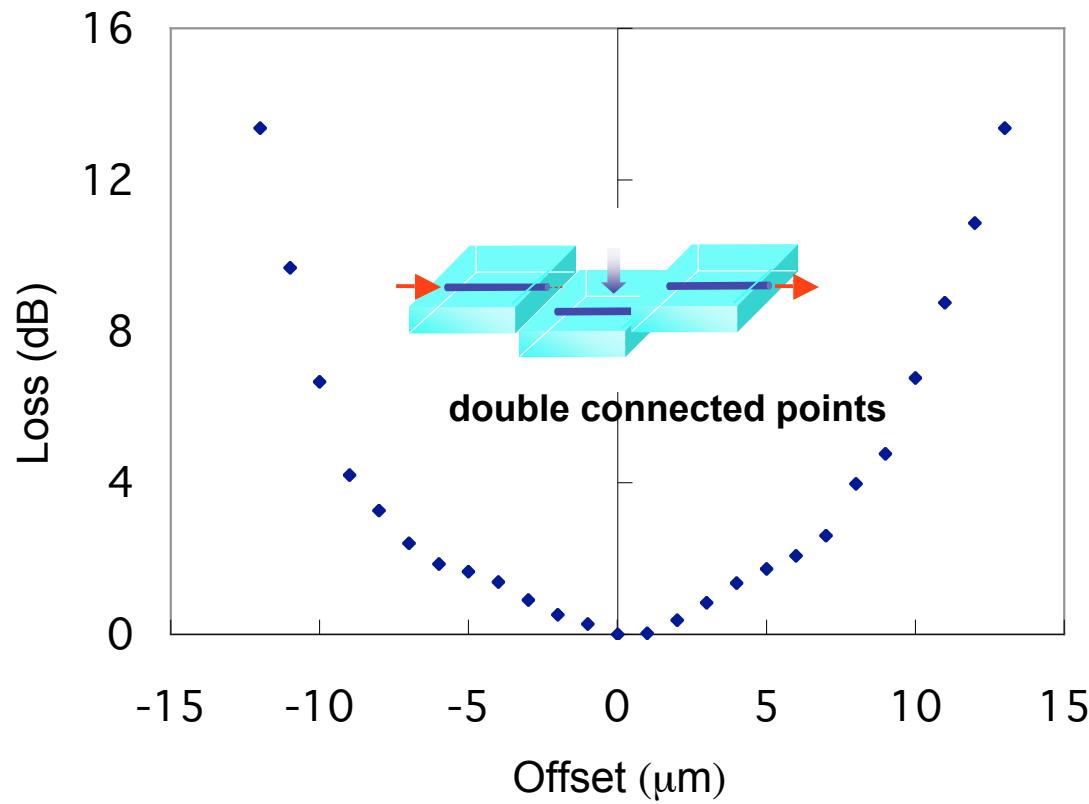
Separation loss



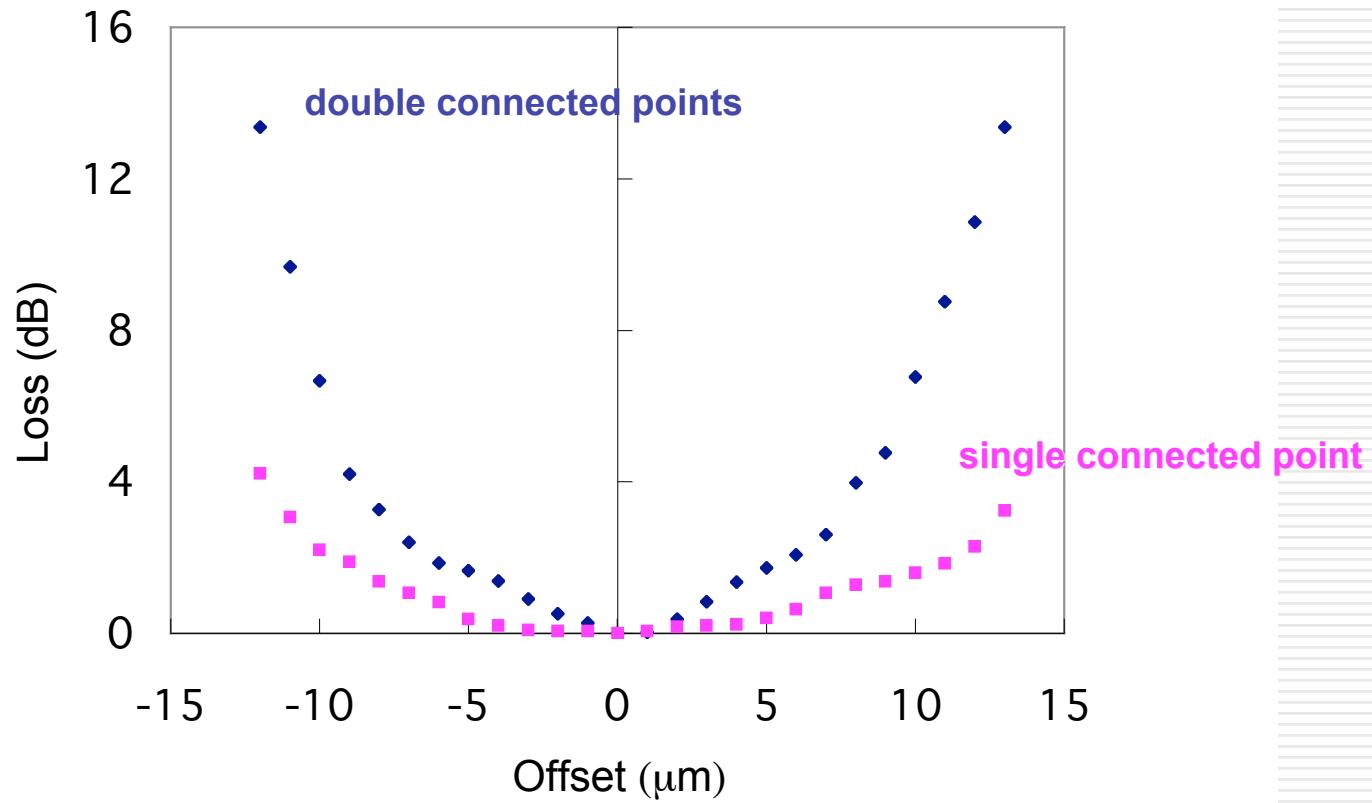
Lateral offset loss



Lateral offset loss

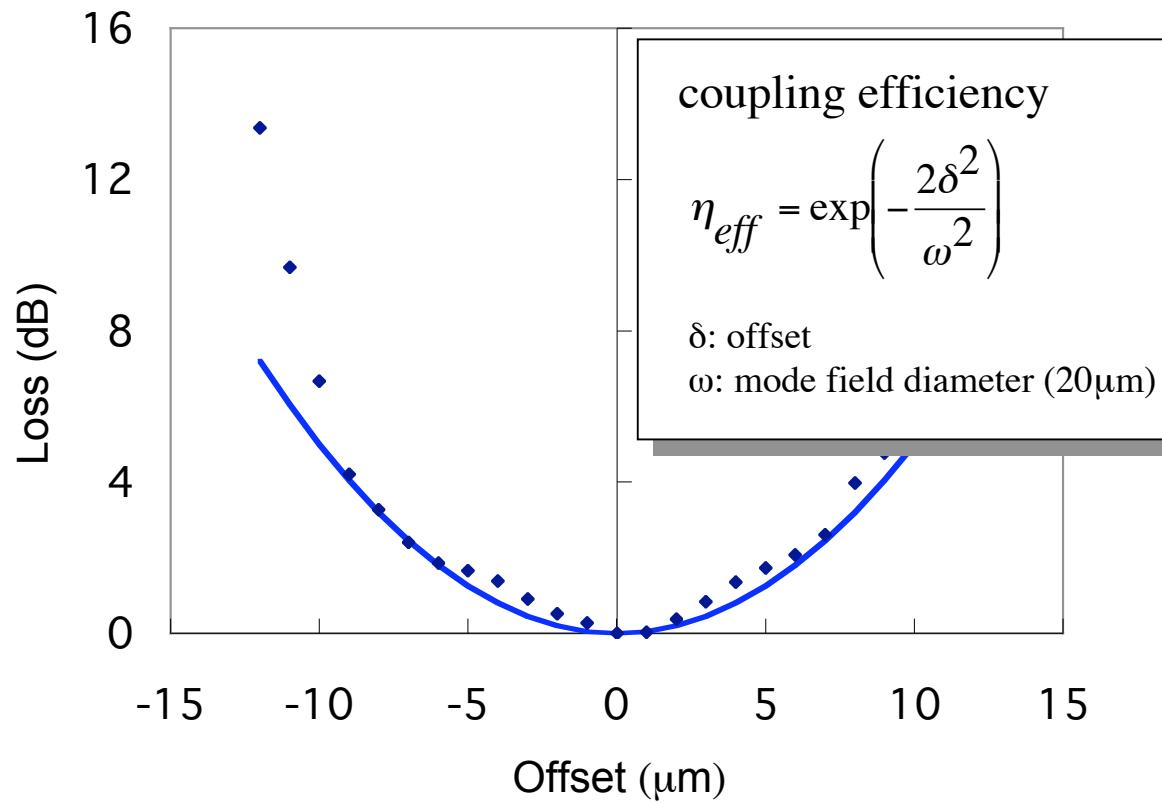


Lateral offset loss

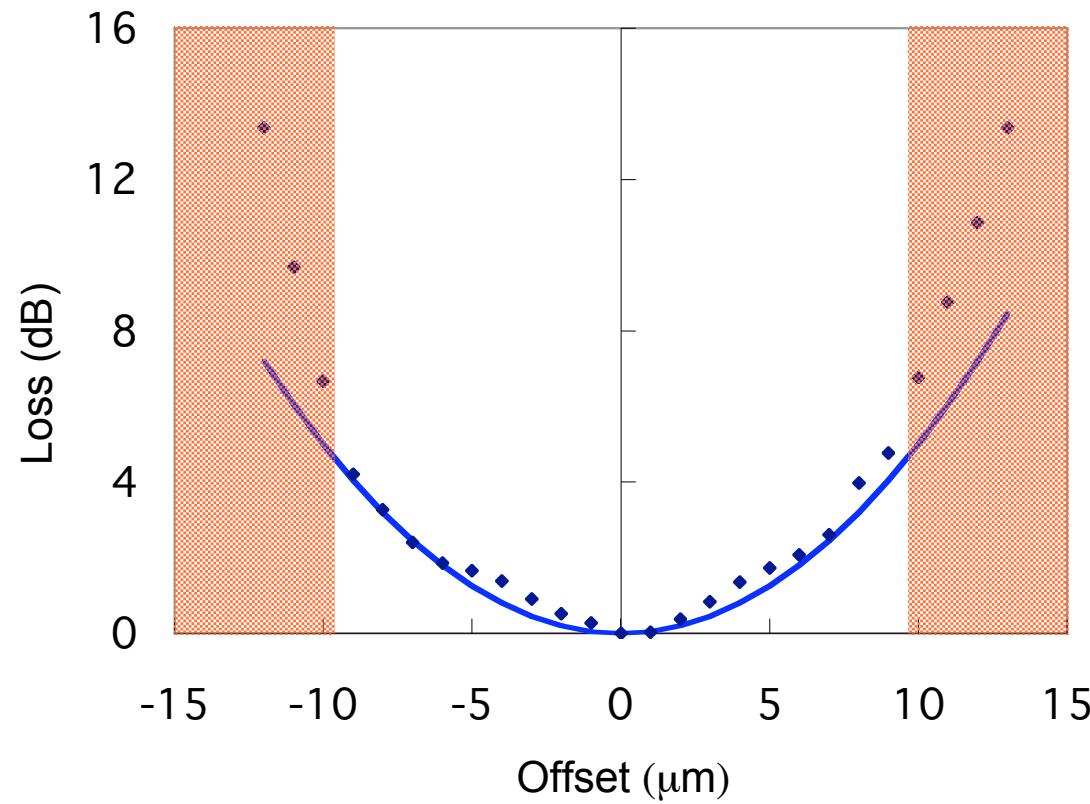


anharmonic relation between the offset and the loss

Lateral offset loss



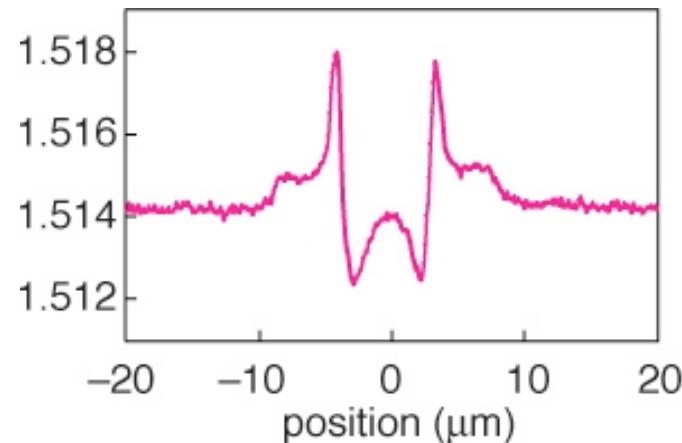
Lateral offset loss



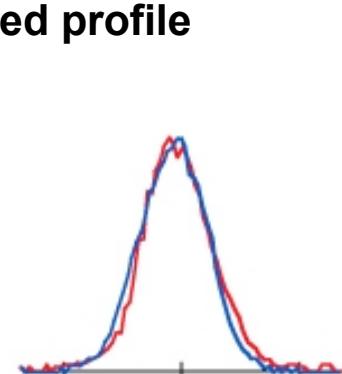
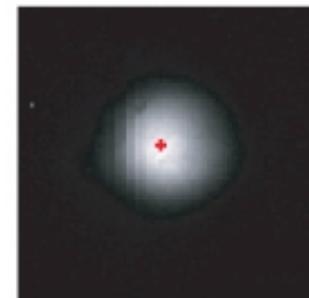
discrepancy between the data and the theoretical curve

Lateral offset loss

refractive index profile



near field profile



**the discrepancy is due to a non-Gaussian distribution
of refractive index profile of the waveguides**

contents

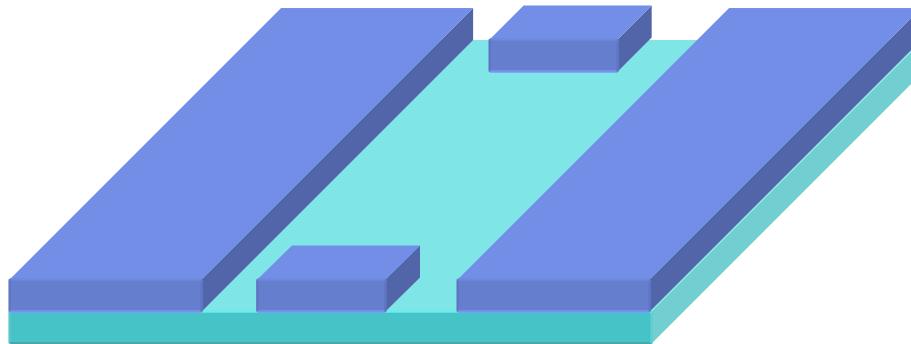
introduction

waveguide wiring

vibration sensor fabrication

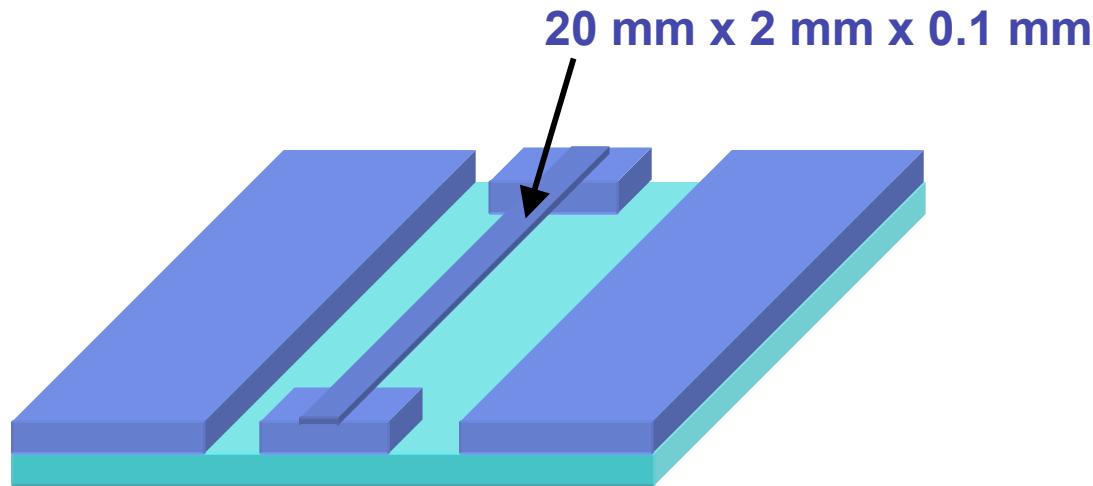
vibration measurement

Sensor fabrication



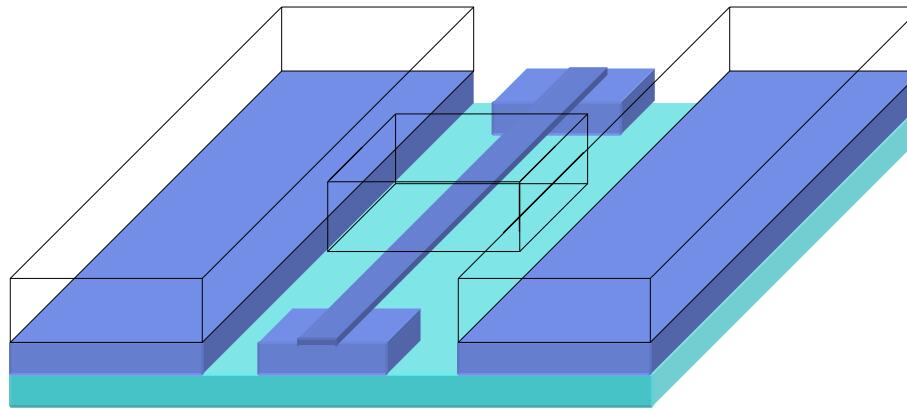
**substrate: sodalime glass
(cut from slide glass)**

Sensor fabrication



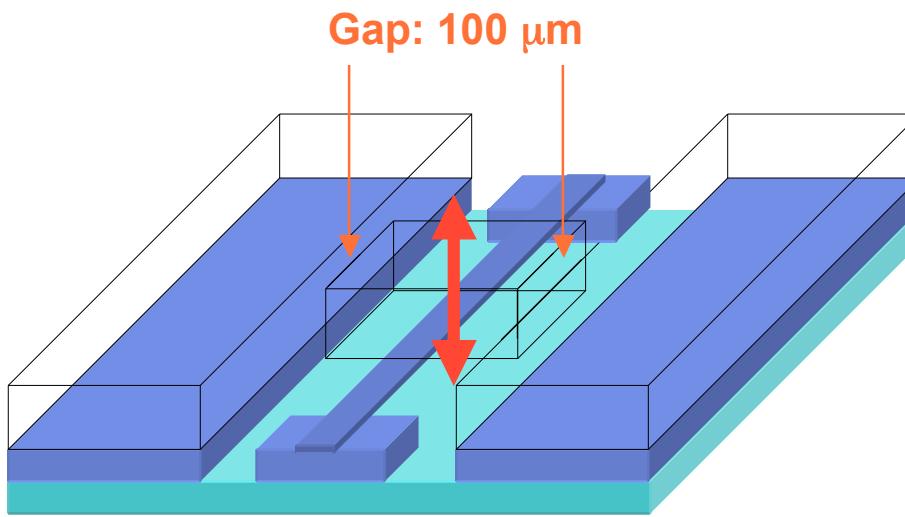
**suspended beam: borosilicate glass
(cut from cover slip glass)**

Sensor fabrication



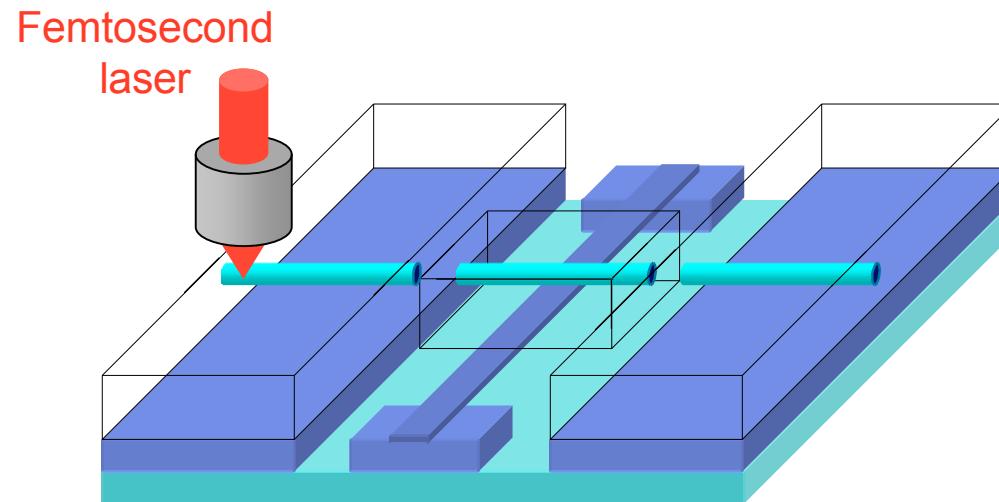
**glasses to write waveguides:
sodalime glass**

Sensor fabrication



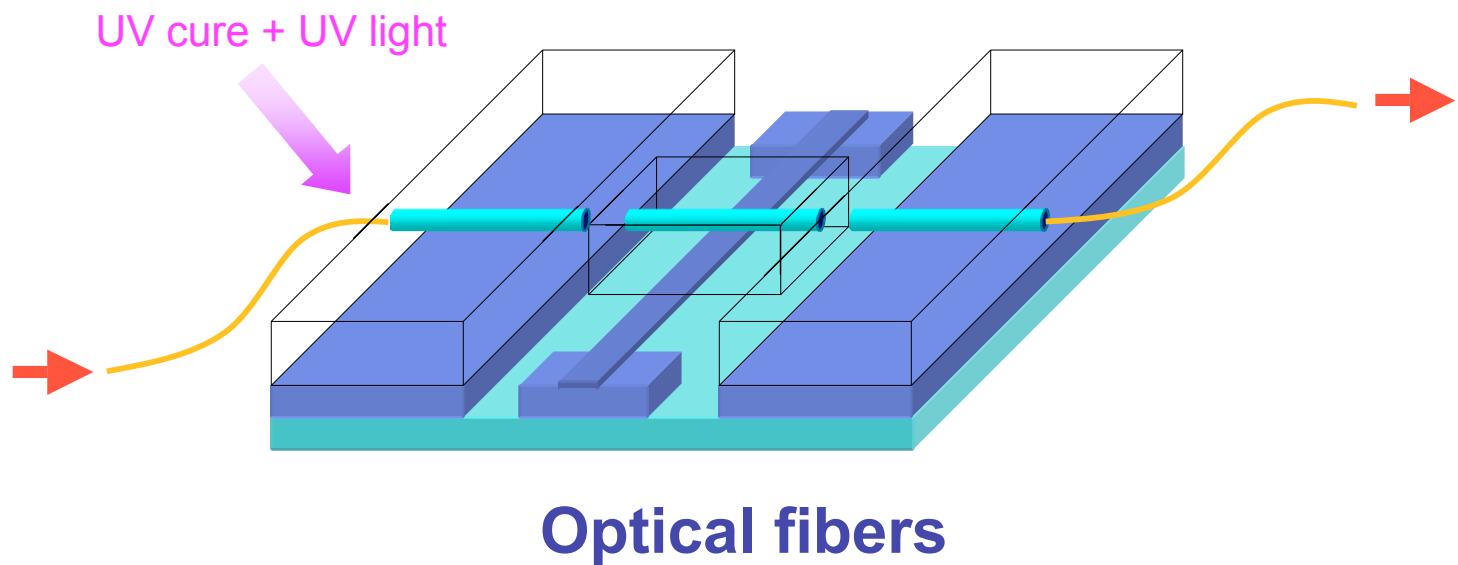
center glass: movable

Sensor fabrication

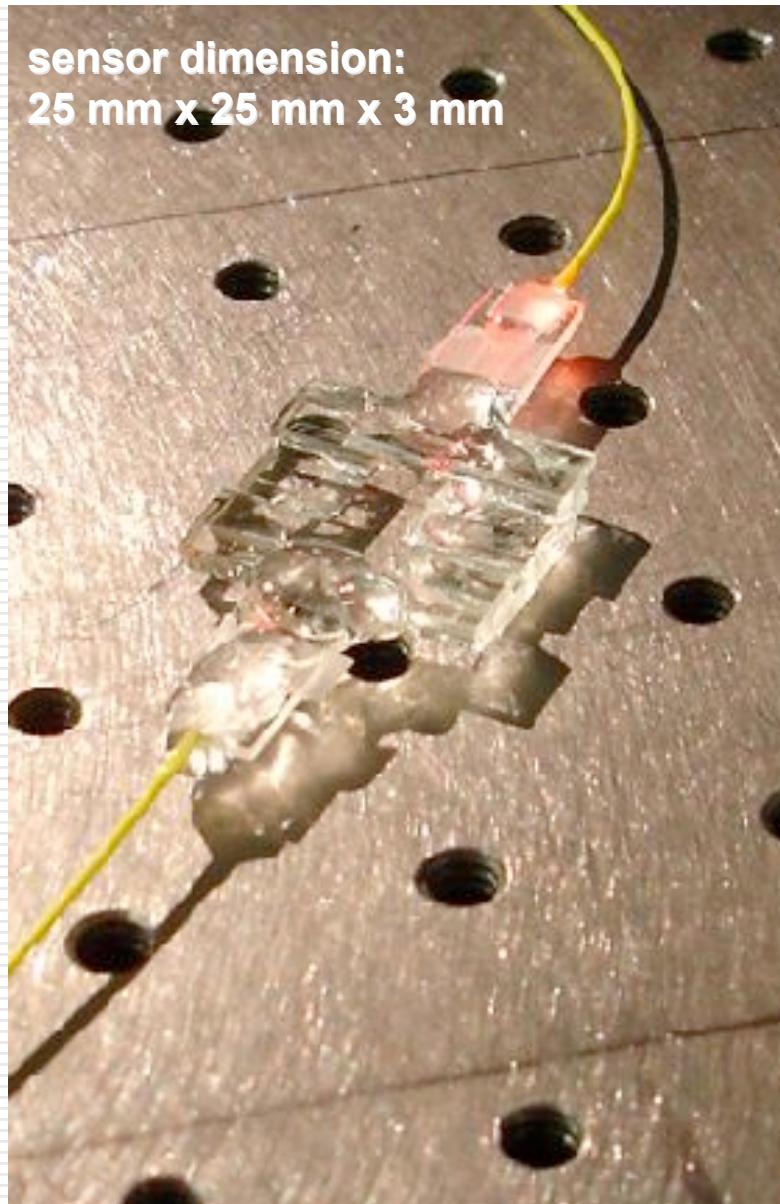


Writing waveguides

Sensor fabrication



Sensor fabrication



contents

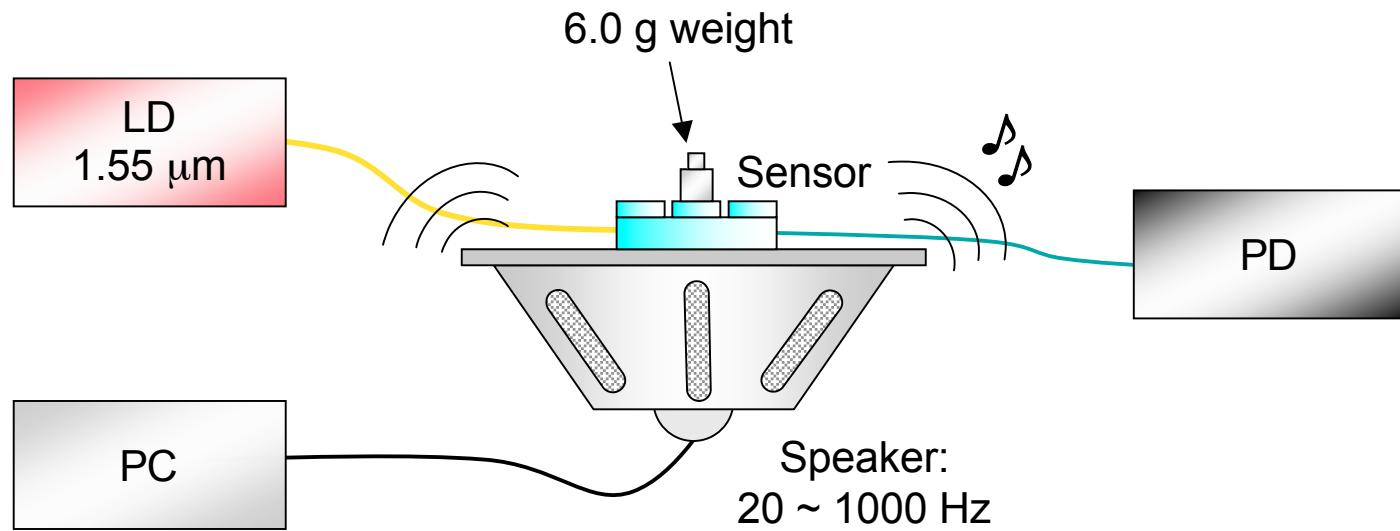
introduction

waveguide wiring

vibration sensor fabrication

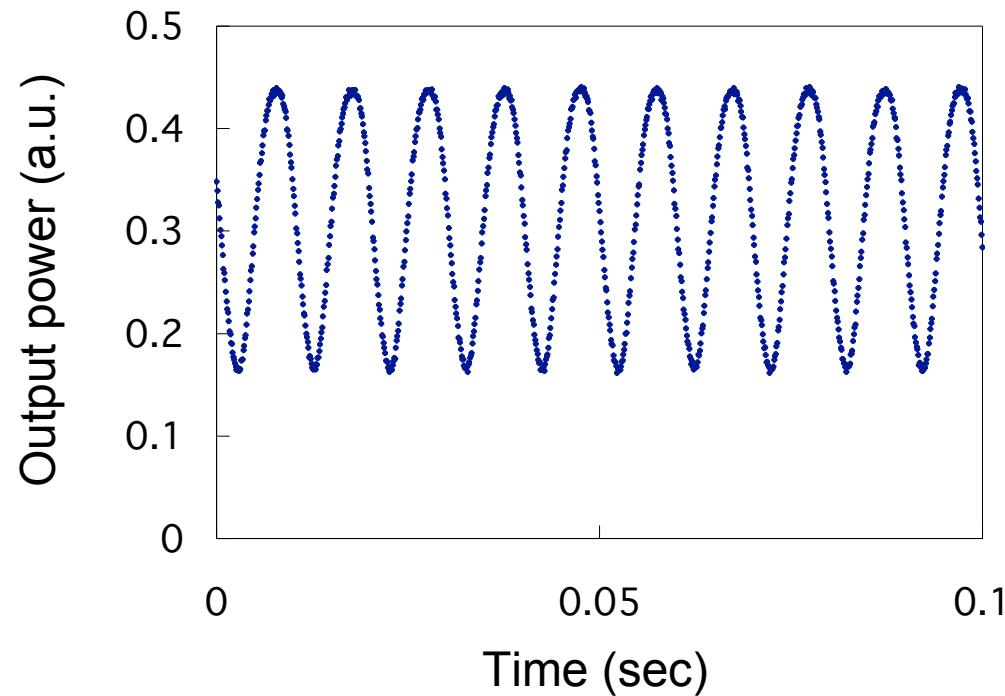
vibration measurement

Vibration measurements



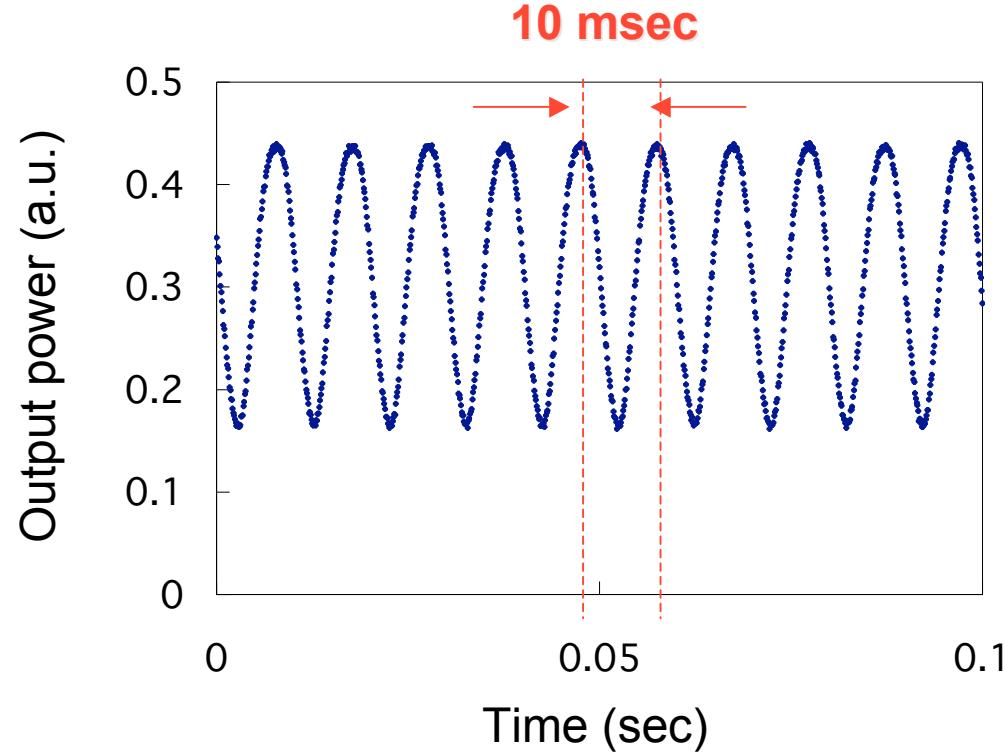
Temporal response of output signal

Input frequency of the sound 100 Hz

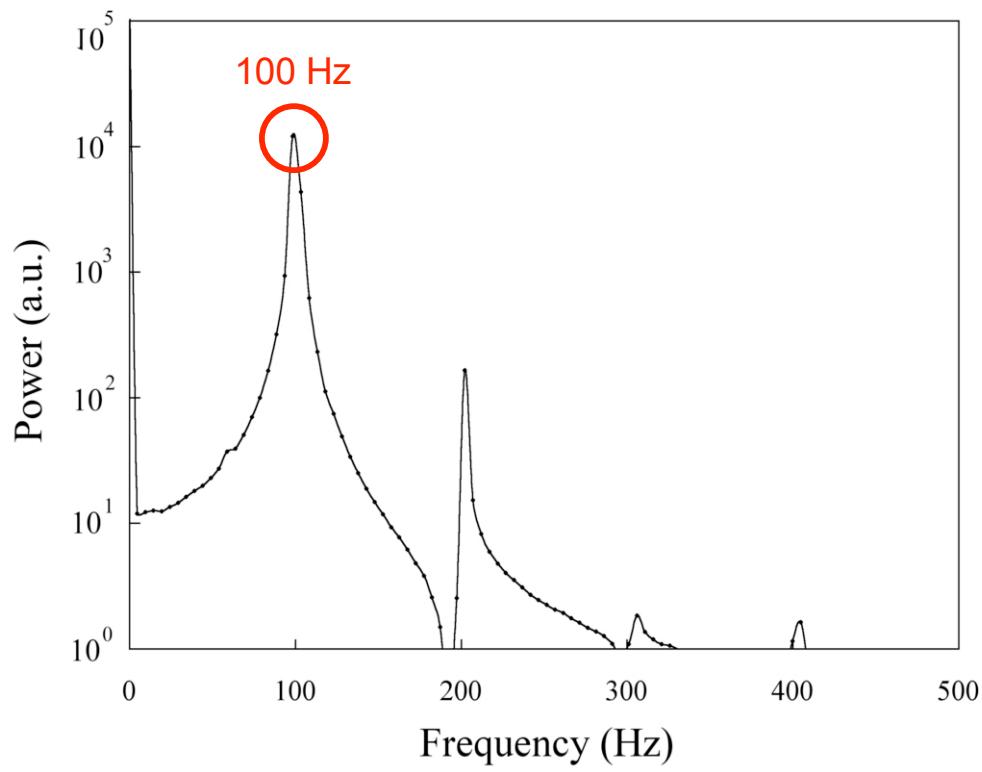


Temporal response of output signal

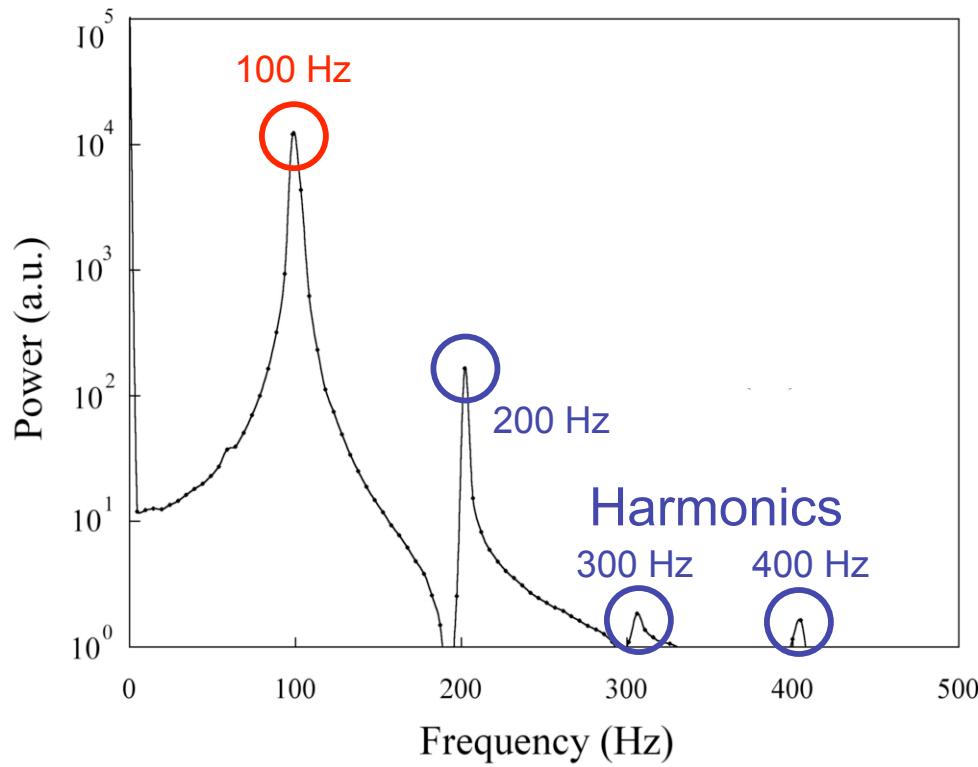
Input frequency of the sound 100 Hz



FFT spectrum of output signal

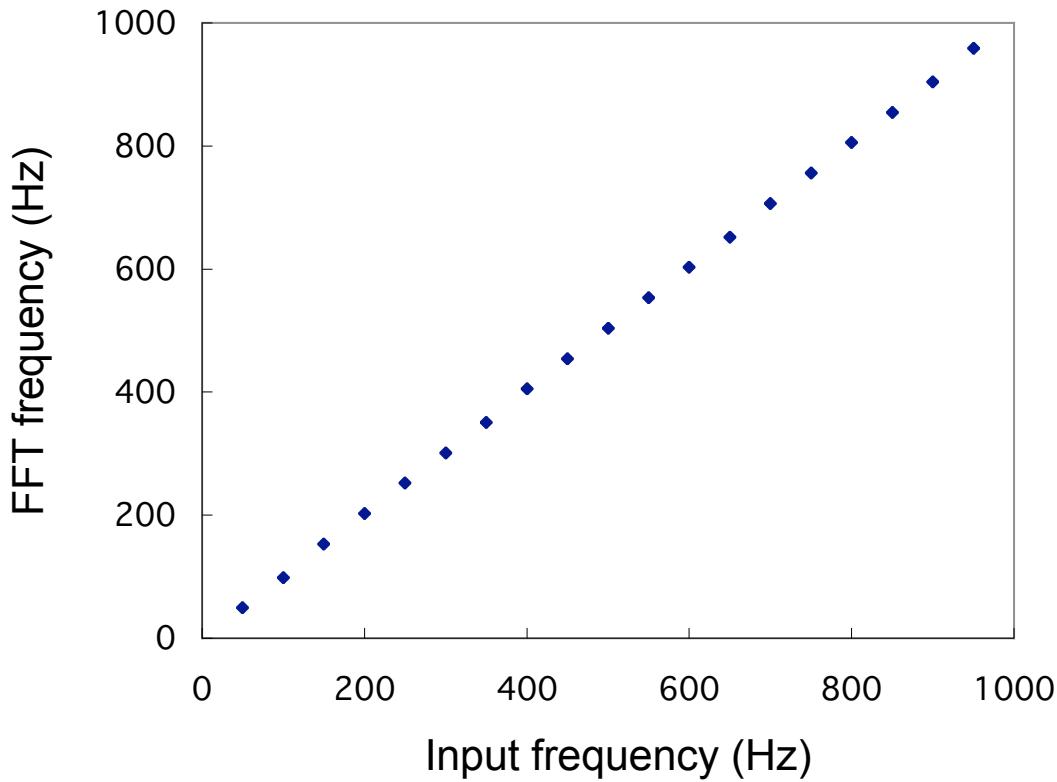


FFT spectrum of output signal



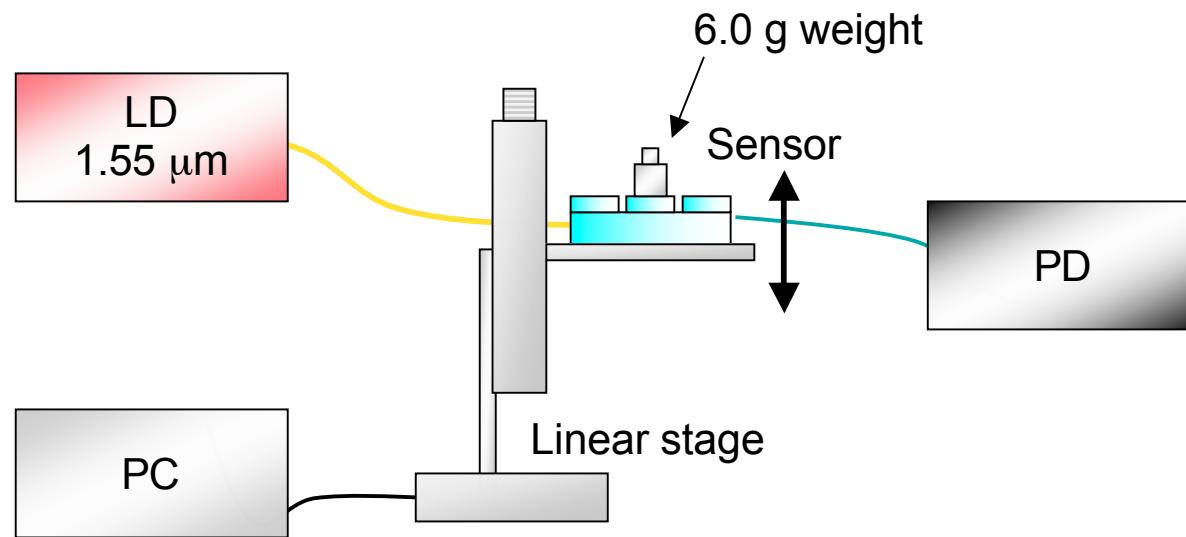
The harmonics come from anharmonic relation between the loss and the offset.

Frequency response

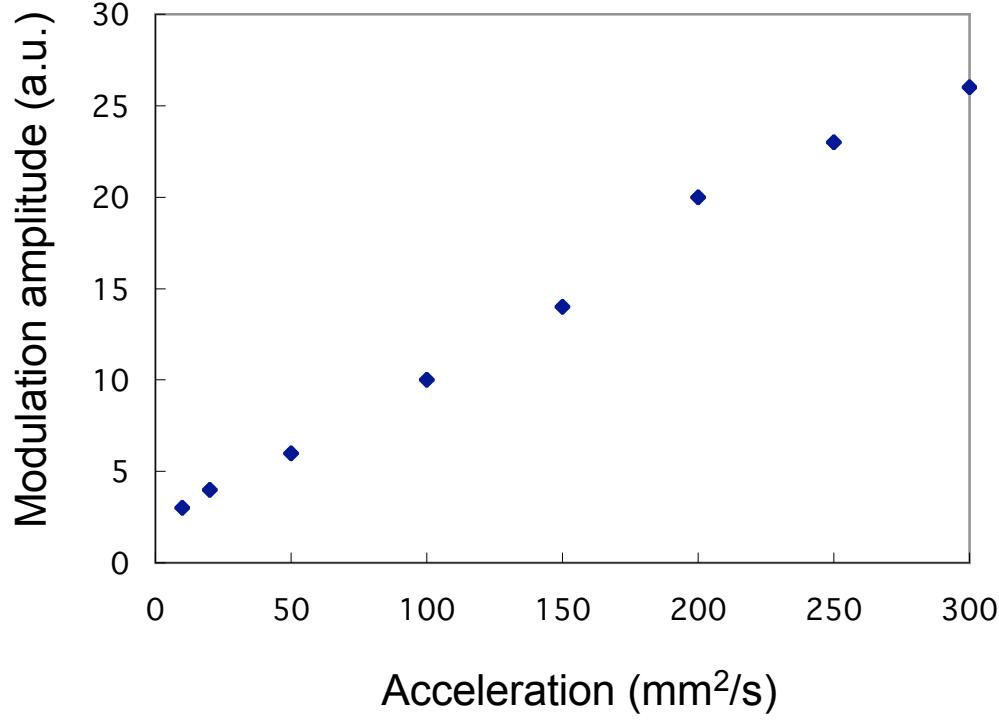


linear relationship between the input frequency and the measured frequency

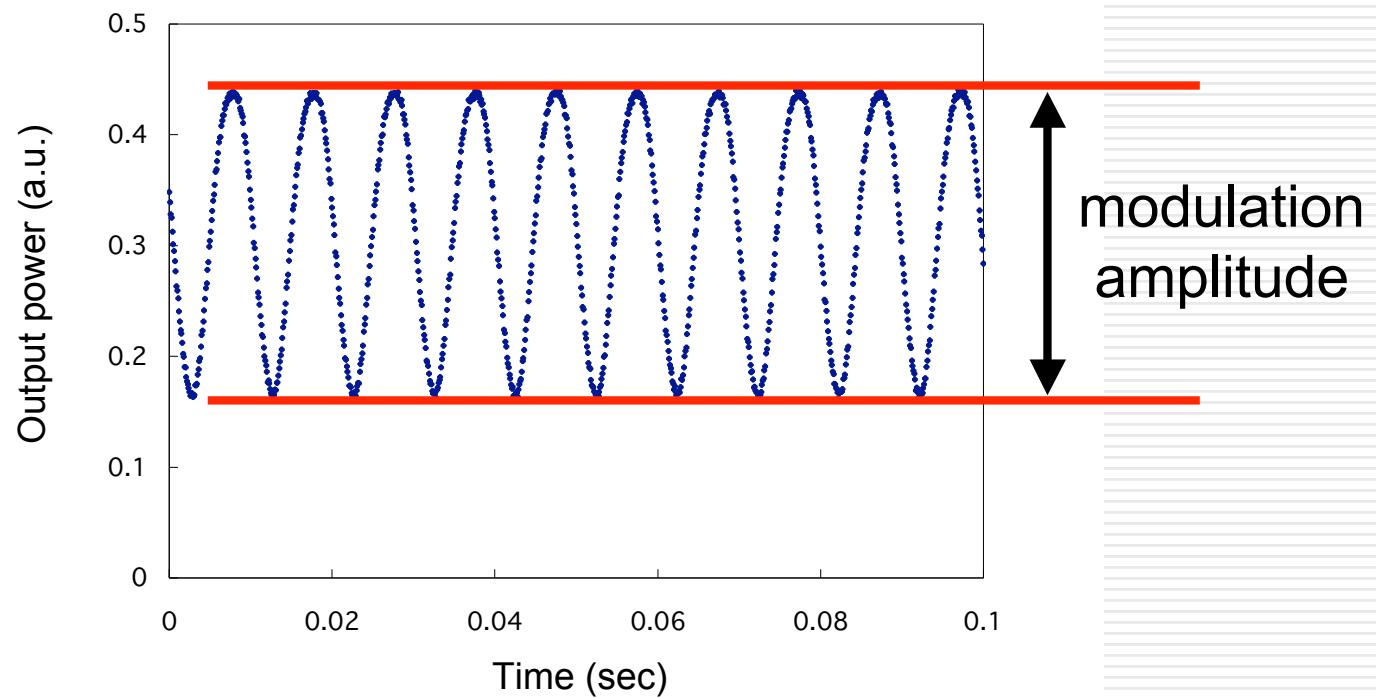
Acceleration measurements



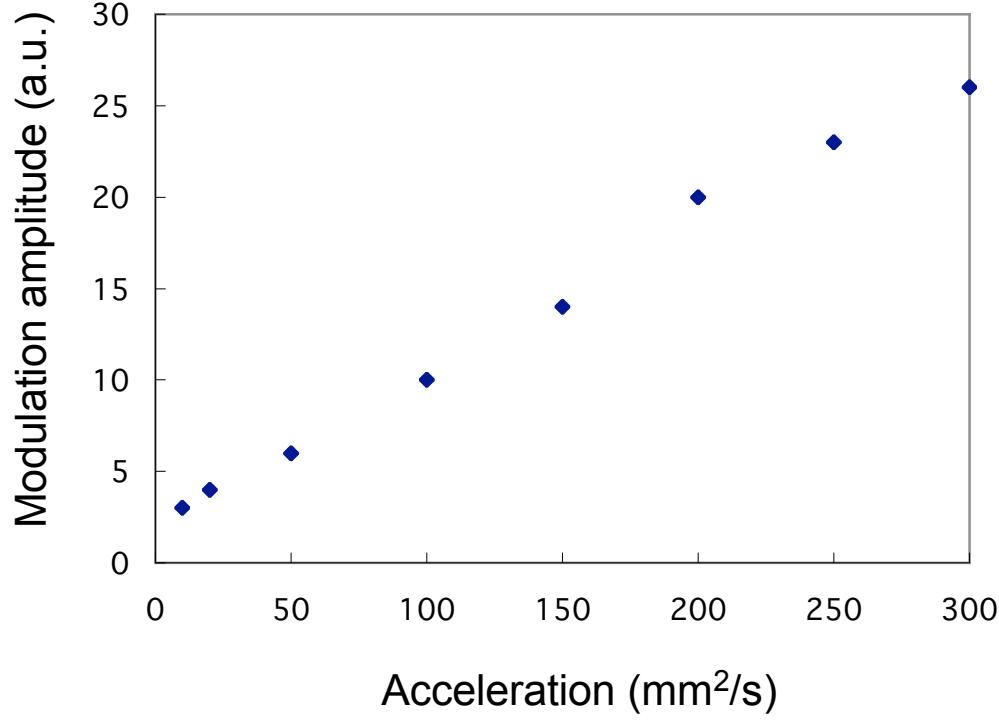
Acceleration sensitivity



Input frequency dependence on modulation amplitude

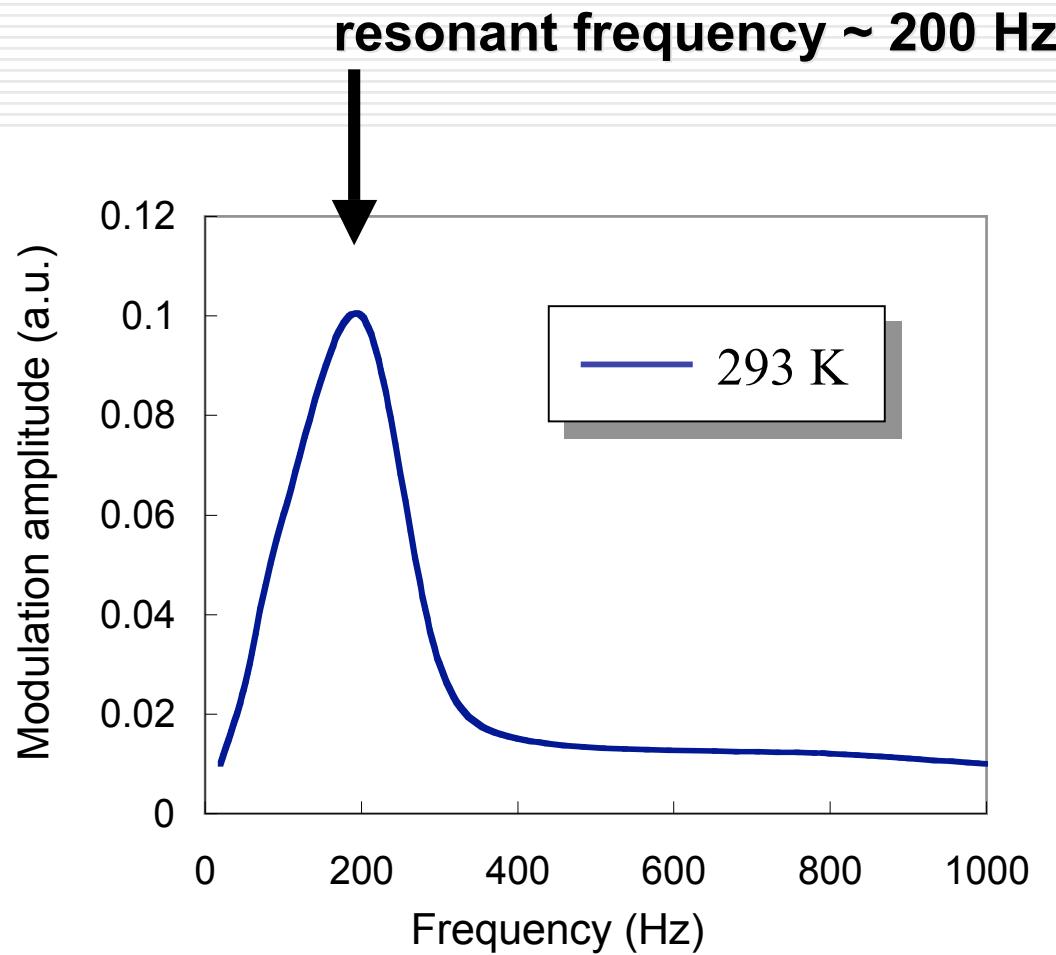


Acceleration sensitivity

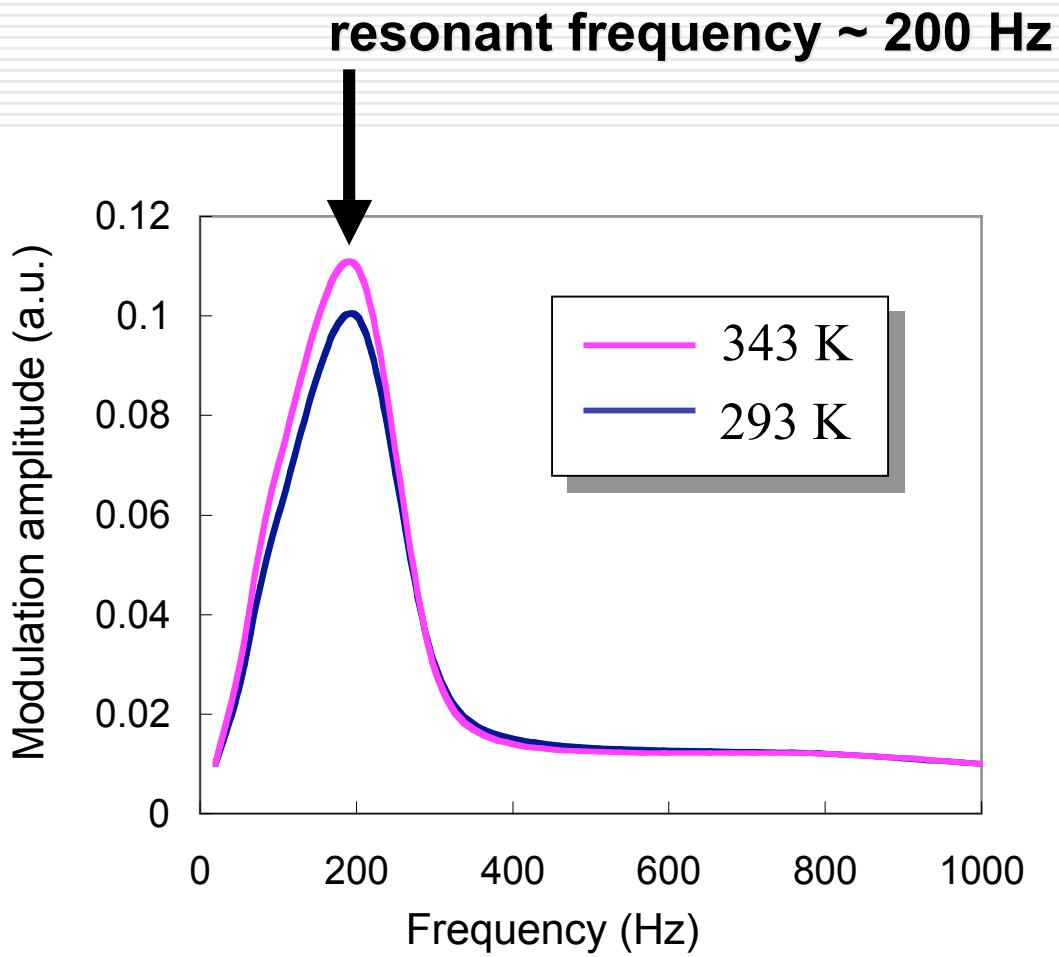


acceleration sensitivity < 0.01 g

Input frequency dependence on modulation amplitude



Temperature dependence on modulation amplitude



negligible temperature dependence

Conclusions

The waveguides wiring

easy samples preparation

sub micron sensitivity for lateral offsets

the ultimate passive alignments

Conclusions

The waveguides wiring

easy samples preparation

sub micron sensitivity for lateral offsets

the ultimate passive alignments

The Novel vibration sensors

immune to electromagnetic fields

high sensitivity and negligible temperature dependence

affordable fabrication costs compared to FBG sensors