Applications of Fibre Laser Based Sensors - *Hydrophone Systems*

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Outline

Background

Fibre laser hydrophones

Fibre laser fabrication

DFB fibre laser hydrophones

Composite cavity fibre laser hydrophones

Conclusion

Background

Fibre Hydrophones

Hydrophone

- *Detect acoustic wave under water*
- *Conventionally made from piezo-electric material now widely used*

Important parameters

- *Sensitivity*
- *Frequency response*
- *Dynamic range*
- *Environment Independent operation*

to temperature and hydrostatic pressure within ranges of interest

Fibre Hydrophones

Sensitivity depends on:

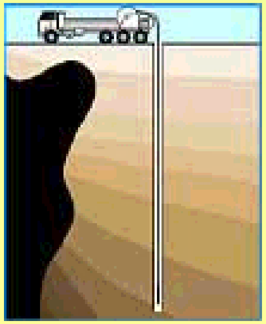
- *Young's modulus and Poisson ratio*
- *Stress-optic coefficient*
- *Size and shape of coating, mandrel and encapsulating material*
- *Length of sensing fibre*

Dynamic range depends on

- *Optoelectronic component, interrogation scheme, system design*

Fibre Hydrophone Applications

- *Geophysical exploration, metrology*
  - *Borehole monitoring*
  - *Fault monitoring - mines, buildings, dams, bridges*
  - *Seismic activity monitoring - earthquakes etc*
  - *Ocean bottom cable (OBC) AOF system*



- *Industrial Systems*
  - *Civil, chemical, medical applications*

- *Military*

Fibre Hydrophone Applications

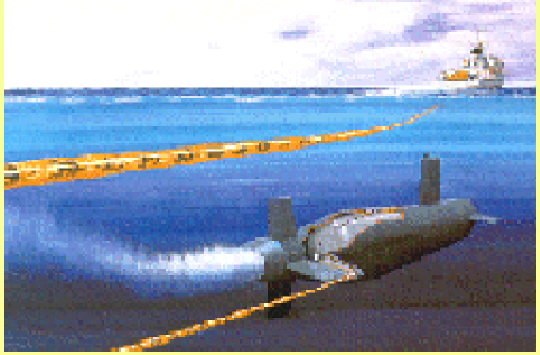
Thin towed array technology

Surface mounting sensor array

Deployable or fixed seabed sensors

Towed array processing

All technologies associated with underwater sensors and signal processing.



Key Fibre Hydrophone Techniques

Head design

Interrogation / demodulation

Multiplexing

Noise and polarisation fading mitigation

Data acquisition and processing

System integration

Fibre laser hydrophones

Fibre laser hydrophones

Using new techniques

FBG & LPFG

DBR and DFB fibre laser

New Fibre laser designs

DAQ & DSP

Fibre laser hydrophones

Small size

Narrower line width (< few MHz) & Long coherent length

Low intensity and phase noises

High SNR and large dynamic range potential

More power per bandwidth than passive fibre & grating sensors

Remote optical pumping & interrogation

Fabrication simplicity and low cost

High multiplexing capability

Fibre laser hydrophones

Key fibre laser characteristics

Linewidth & coherence length

Intensity & frequency response

Polarisation

Output power

RIN, Relaxation oscillations

Fibre laser hydrophones

Fibre Laser

both source and sensing element

Laser structure

Gain medium

- *Erbium-doped fibre*

Feedback mechanism

- *FP cavity -- Mirror pairs*
- *DBR -- FBG pair*
- *DFB -- Phase-shifted grating*
- *CC -- Primary cavity + external feedback*

Fibre laser fabrication

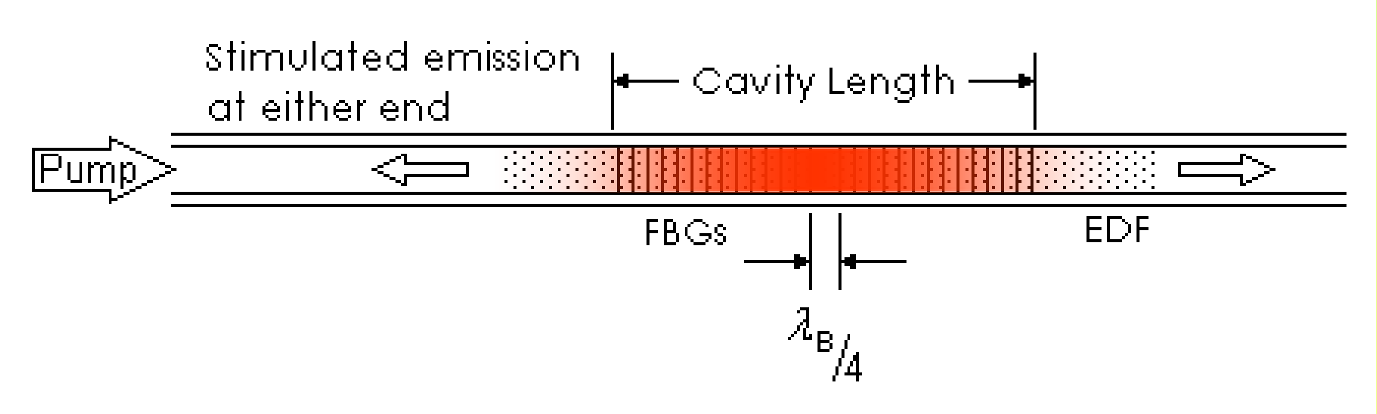
Fibre laser fabrication

Various fibre laser types for hydrophones

- ***DBR fibre lasers***
- ***DFB fibre lasers***
- ***Composite cavity fibre lasers***
- ***Special design fibre lasers***
- ***Fibre laser arrays***

DFB fibre laser

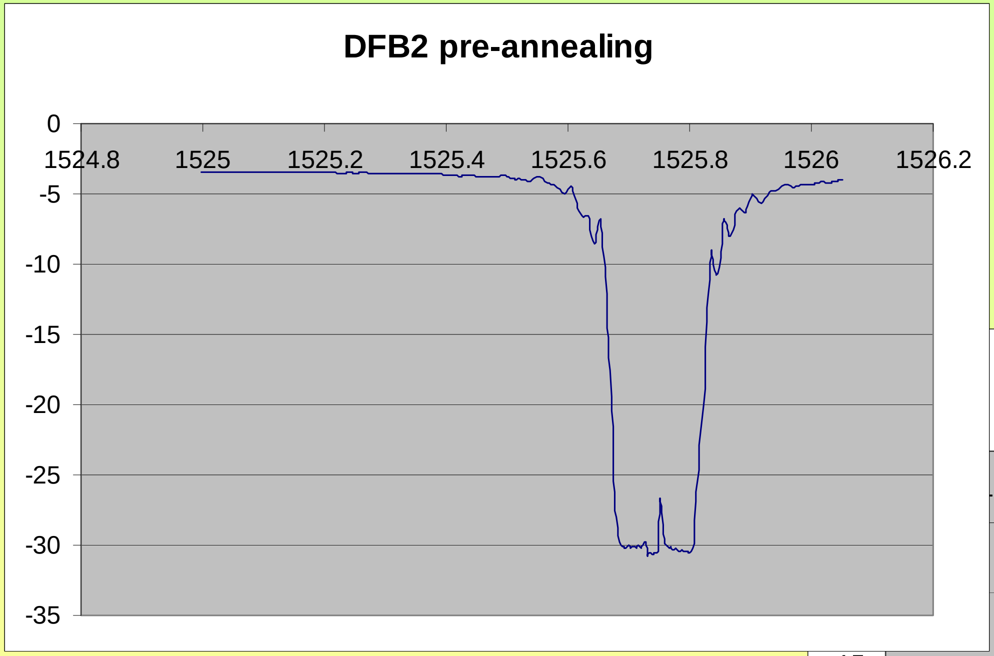
DFB

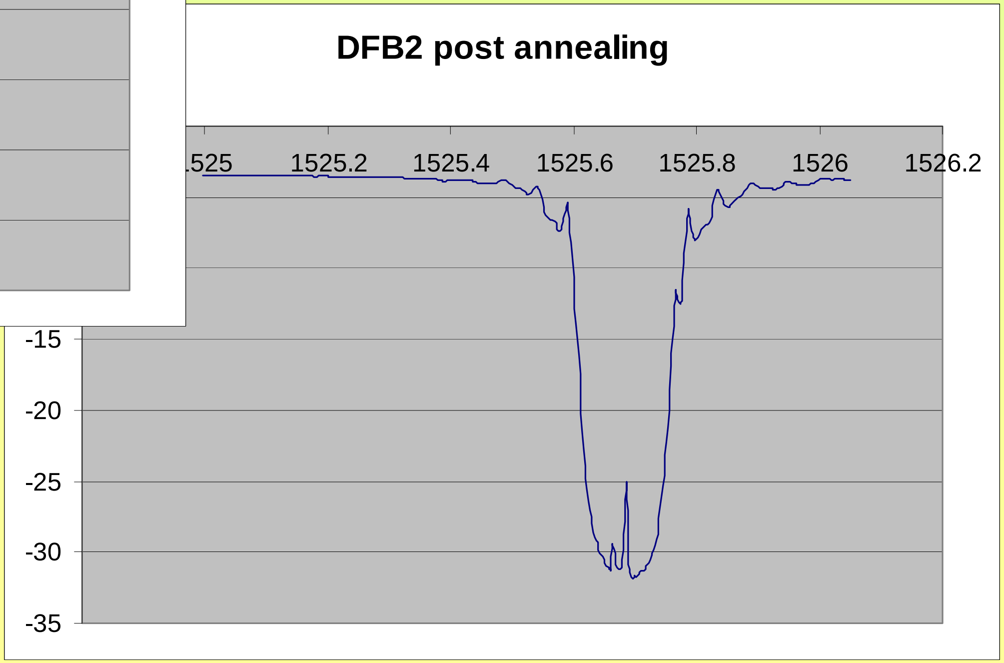


The specific wavelength and line width of the fibre laser are determined by:

- *Transfer function of the gratings (wavelength matching)*
- *Length of the cavity (Fabry-Perot response)*
- *Emission bandwidth of the EDF (gain narrowing).*

DFB fibre laser





DFB fibre laser

Successful development

- Low threshold
- High output power
- Narrow linewidth
- Asymmetric DFB

Work continuing on

- RIN -relaxation oscillation
- New designs

DFB fibre laser

DFB laser successfully fabricated with low threshold

low pump threshold: P_{th} ~ 20mW

single polarisation mode

narrow linewidth ~10kHz

Some issues to avoid

DFB grating mismatching and noise from back end of the fibre laser

- ideal index matching required

Laser self pulsing

- self-pulsing due to clustering

DFB Fibre laser hydrophone

Fibre Laser Hydrophones

Our R&D work

Development of DFBFL & CCFL

Hydrophone system design and implementation

Sensor packaging and testing

Signal acquisition, processing and demodulation

System calibration and data interpretation

DFB Fibre Laser Hydrophone

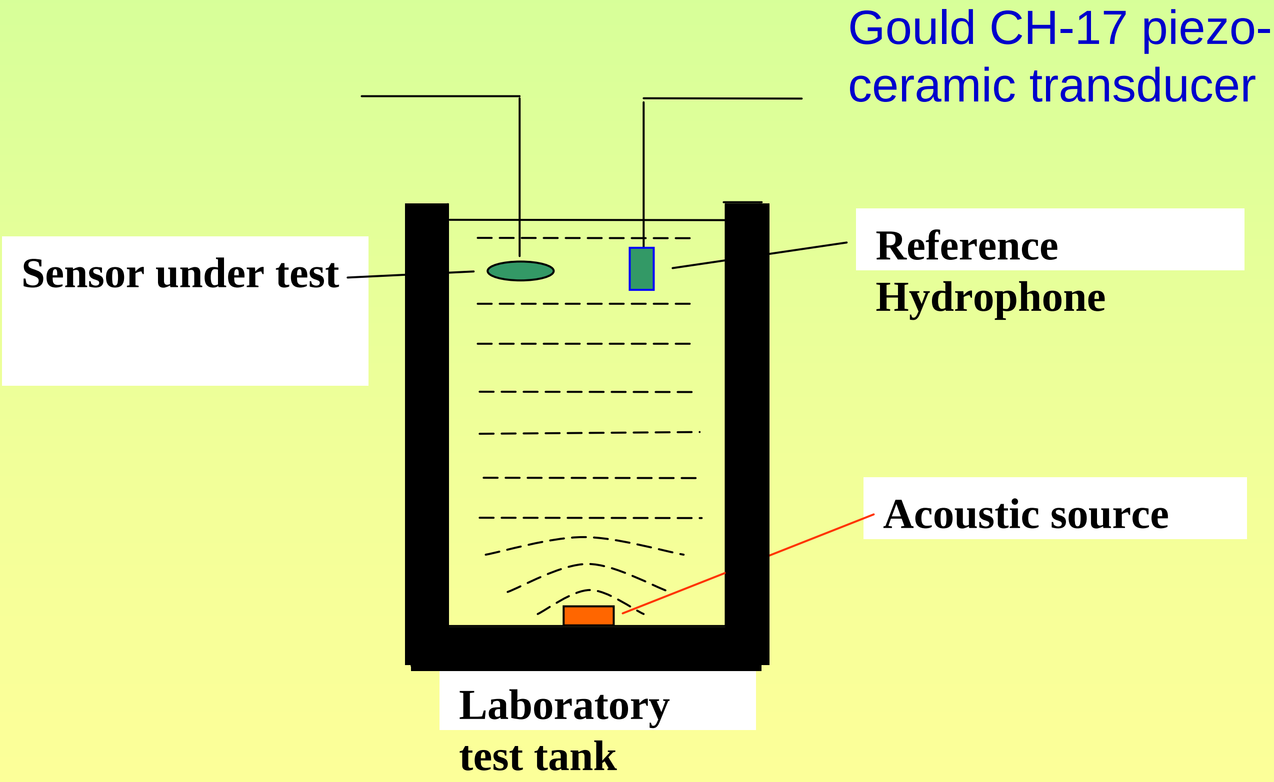
Three experimental methods

Steel water tank + calibrated ceramic hydrophone + digital demodulation (Sydney)

Vibration stage and accellerator + analog demodulation (Shanghai)

Standard in-house and field testing facility (Fuyang)

DFB Fibre Laser Hydrophone



Steel water tank + calibrated ceramic hydrophone + digital demodulation (Sydney)

DFB Fibre Laser Hydrophones

FM -- Interferometric demodulation

very high sensitivity

complicated and delicate

high performance applications

IM -- Direct intensity demodulation

lower sensitivity (high than other IM fibre hydrophones)

simple in design and construction

reliable and robust

DFB Fibre Laser Sensor –IM type

Intensity-modulation type

lower sensitivity

simple in design and construction

reliable and robust

DFBFL Hydrophone –IM type

Basic principles of IM-type of FLS:

1) *Coupled mode equation:*

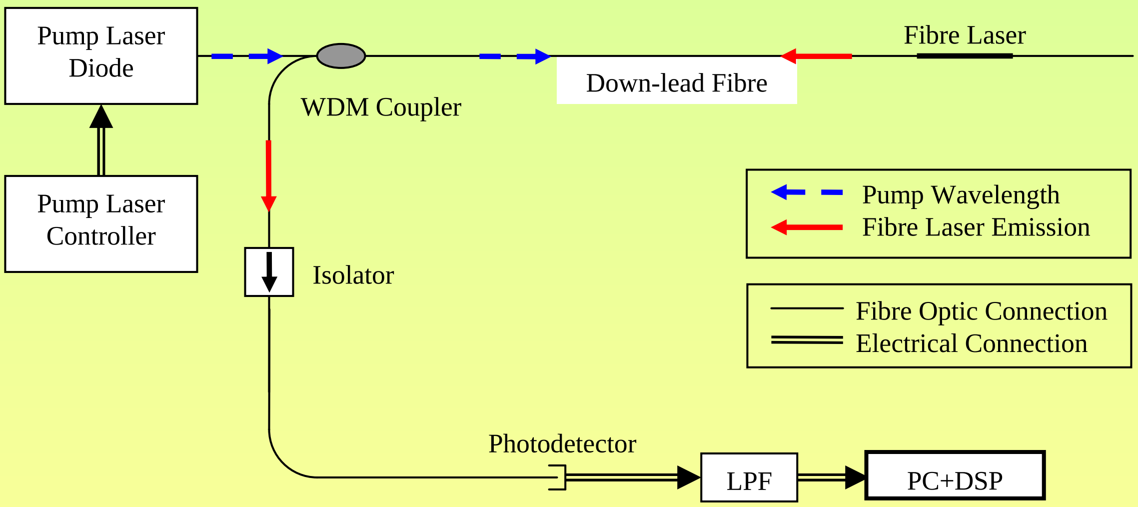
$$\frac{dE^+}{dz} + i\left[\kappa_{dc} + \frac{1}{2}\left(\Delta\beta - \frac{d\phi(z)}{dz}\right)\right]E^+ = -i\kappa_{ac}^* E^-$$

$$\frac{dE^-}{dz} - i\left[\kappa_{dc} + \frac{1}{2}\left(\Delta\beta - \frac{d\phi(z)}{dz}\right)\right]E^- = i\kappa_{ac} E^+$$

acoustic field interacts with the phase shift locally causing $\frac{d\phi(z)}{dz}$ *to vary, leading to power fluctuations.*

2) *Birefringence, resulting from side writing technique, also enables cavity's polarisation conditions to be modulated by external acoustic wave.*

DFB Fibre Laser Hydrophone

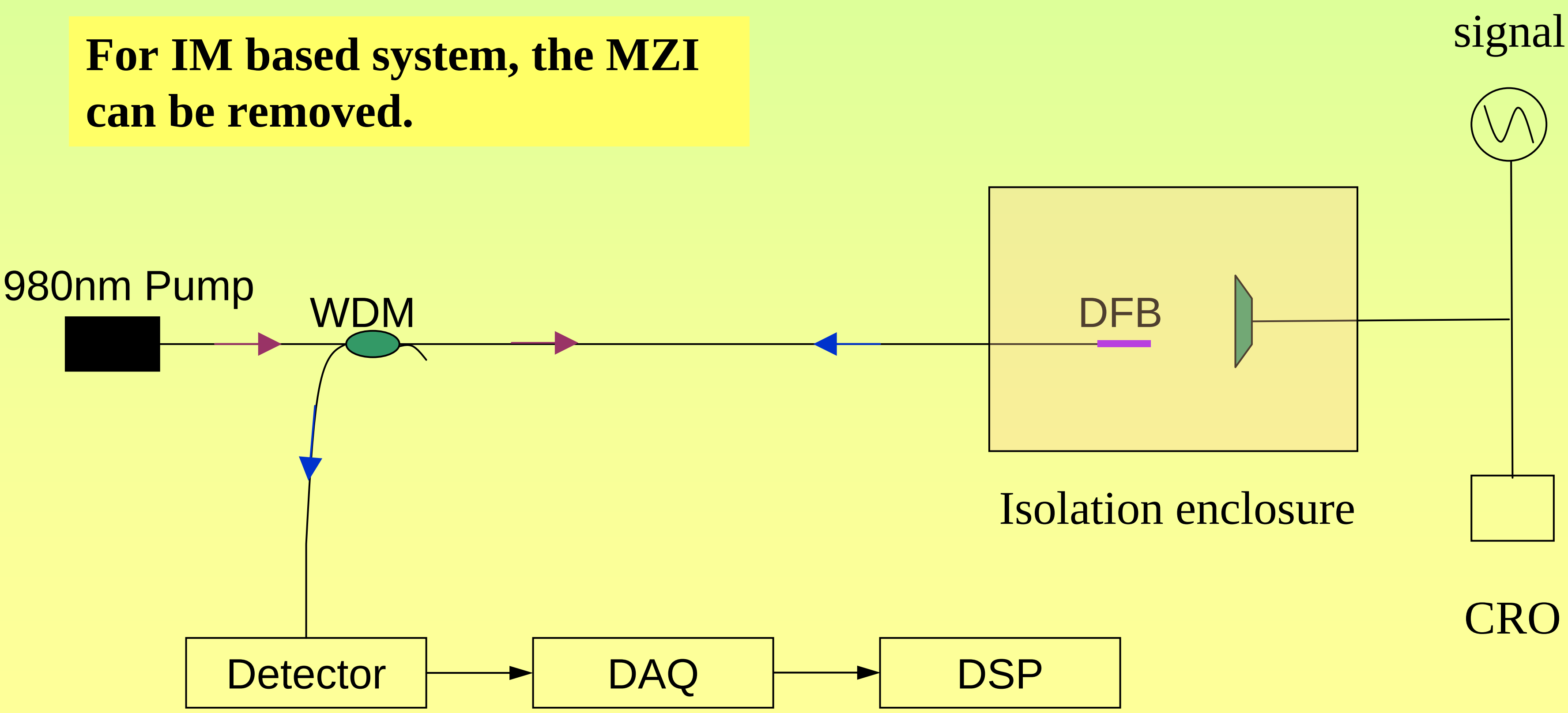


DFB fibre laser based intensity-type hydrophone at high frequencies up to 20kHz.

DFB Fibre Laser Hydrophone

Intensity Modulation (IM) based fibre laser hydrophone:

For IM based system, the MZI can be removed.

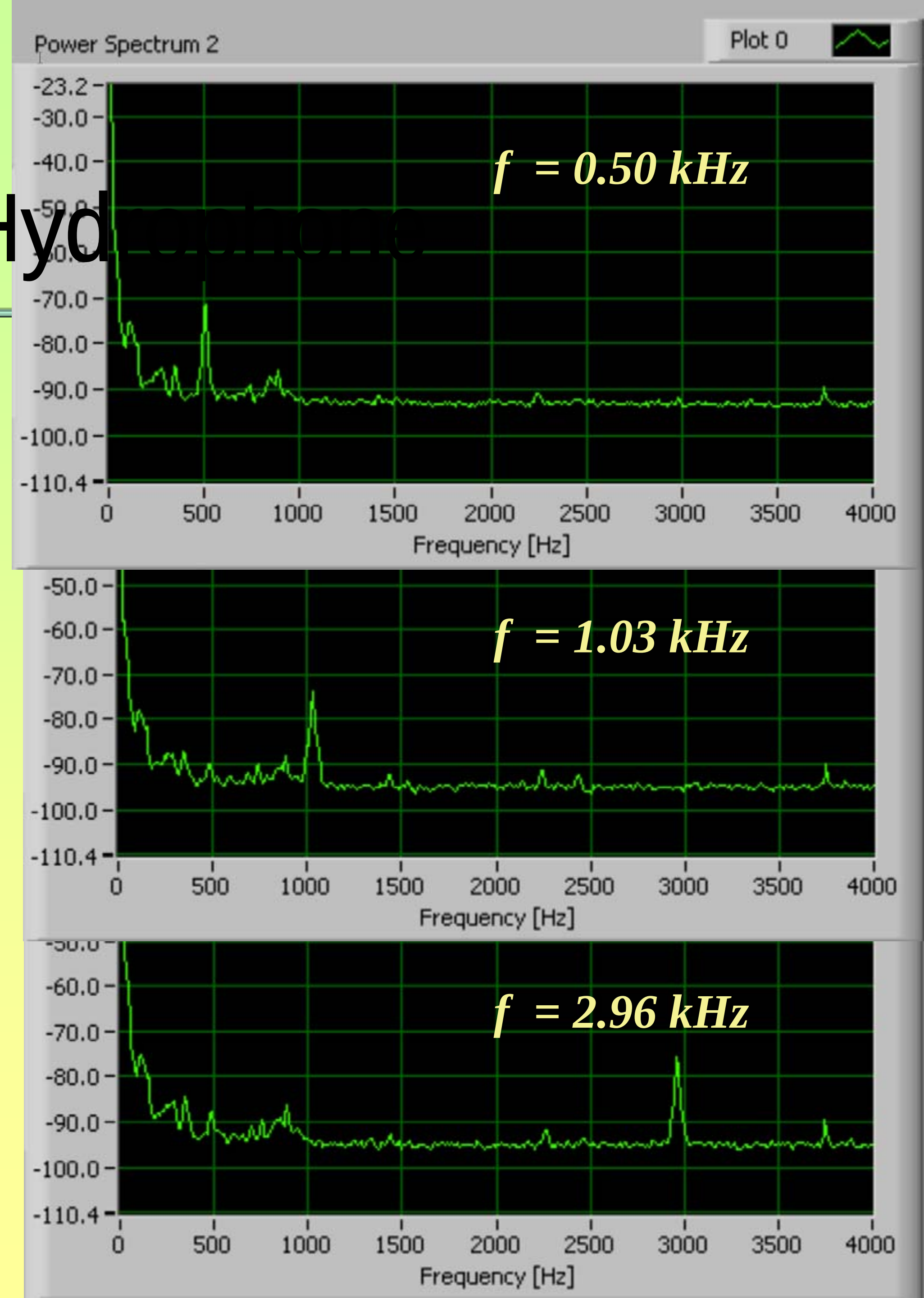


DFB Fibre Laser Hydrophone

Intensity Modulation (IM) based fibre laser hydrophone:

Experimental conditions:

I_p=140mA,
V_s=0.0035V;
N=20000;
f_s=200kHz;
Gain=100kΩ;
HPF=DC;
LPF=100kHz



DFB Fibre Laser Hyd

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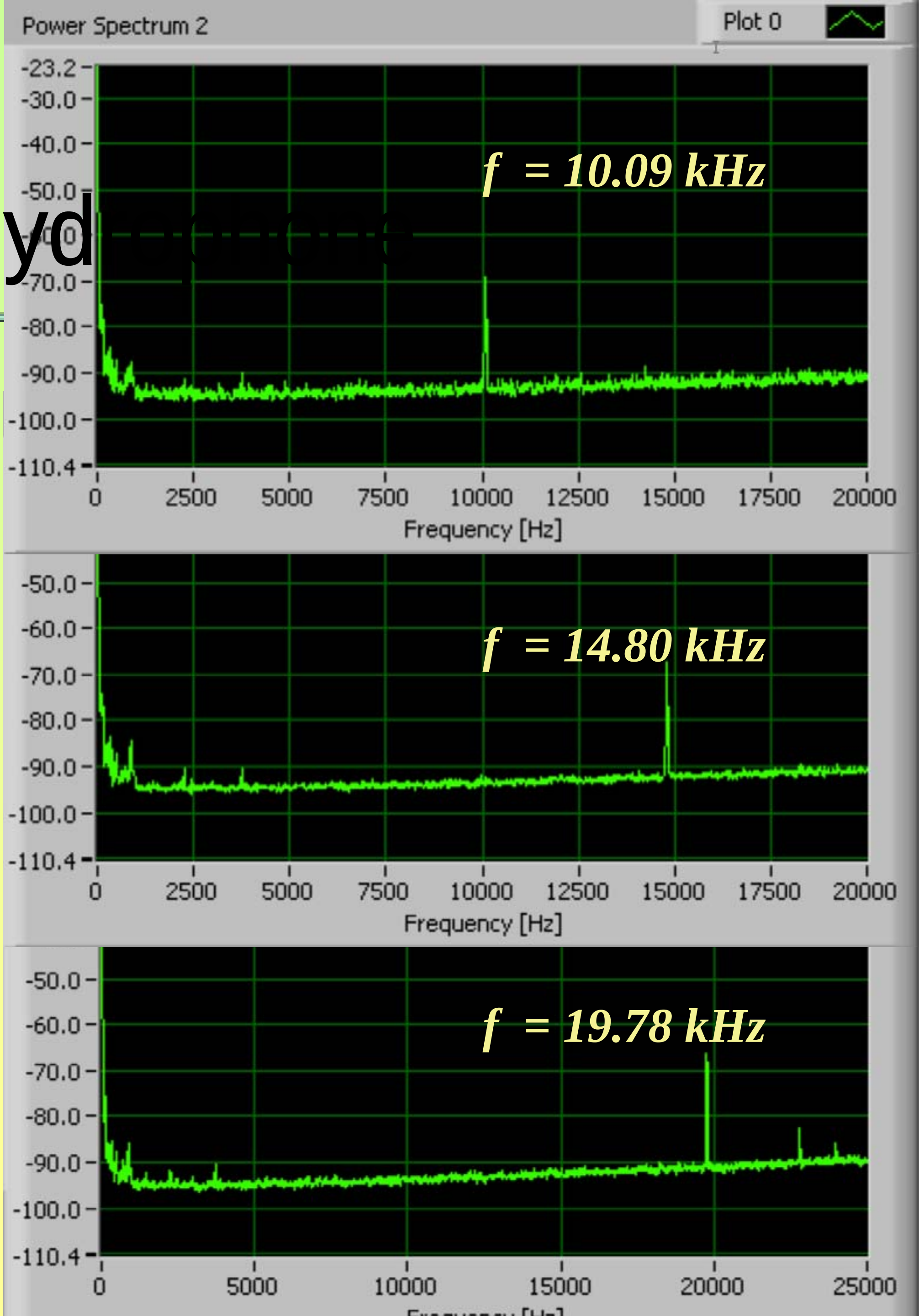


DFB Fibre Laser Hydrophone –FM type

Frequency-modulation type

Very high sensitivity

Delicate demodulate required

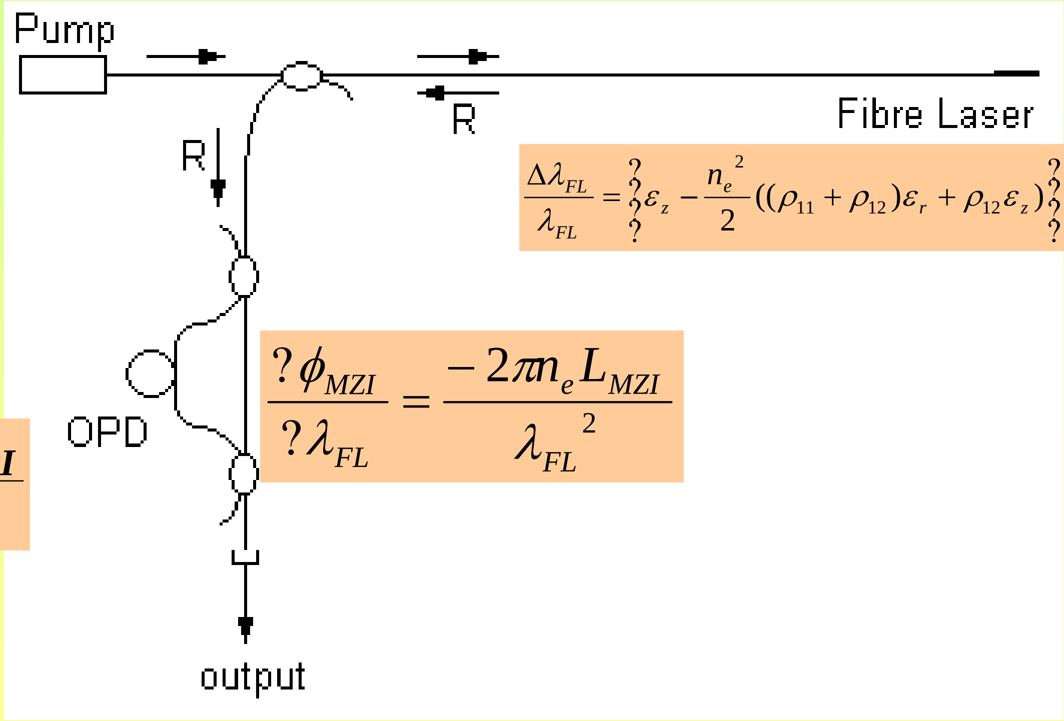
High performance applications

Fibre laser hydrophones

Frequency modulation (FM) based fibre laser sensor:

- ***High sensitivity***
- ***Simple system***

$$\phi_{MZI} = \frac{2\pi n_e L_{MZI}}{c} \nu_{FL} = \frac{2\pi n_e L_{MZI}}{\lambda_{FL}}$$

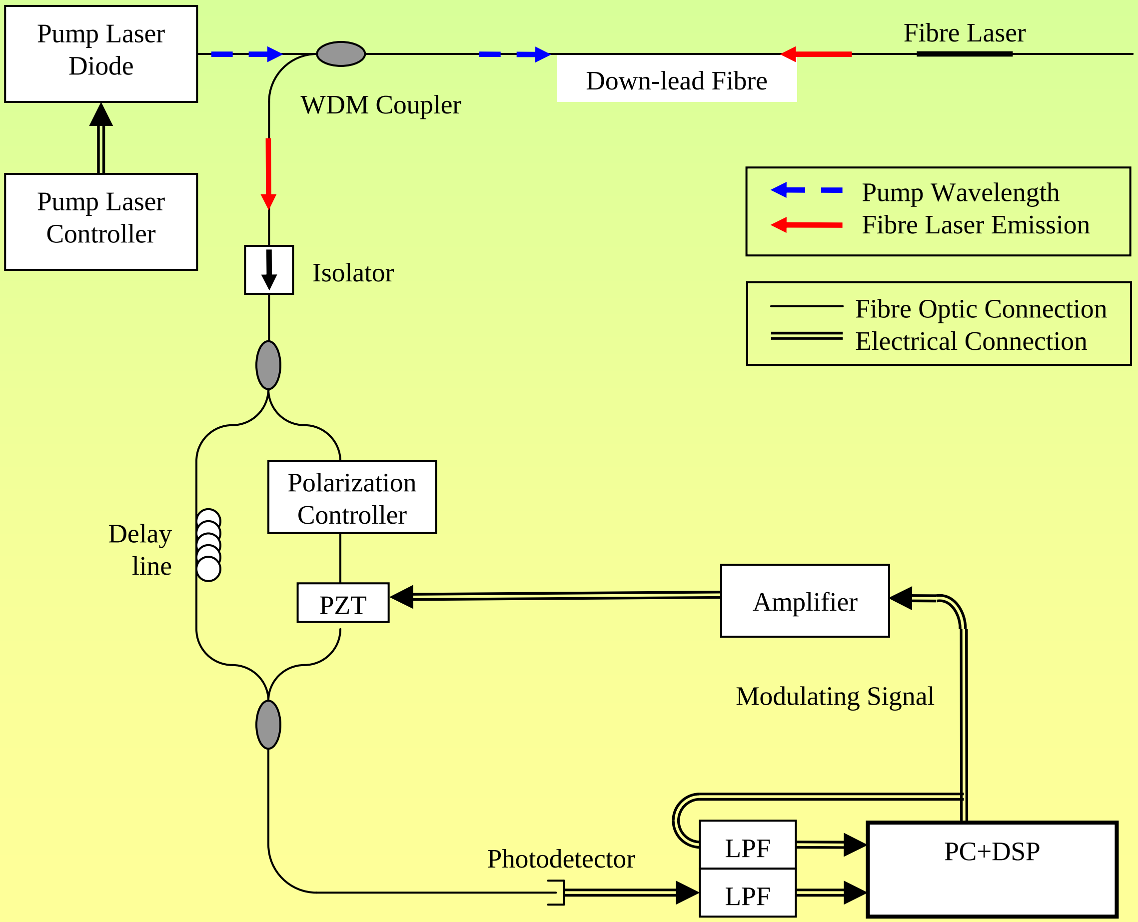


$$\frac{\Delta\lambda_{FL}}{\lambda_{FL}} = \left\{ \varepsilon_z - \frac{n_e^{2}}{2}\left((\rho_{11} + \rho_{12})\varepsilon_r + \rho_{12}\varepsilon_z\right) \right\}$$

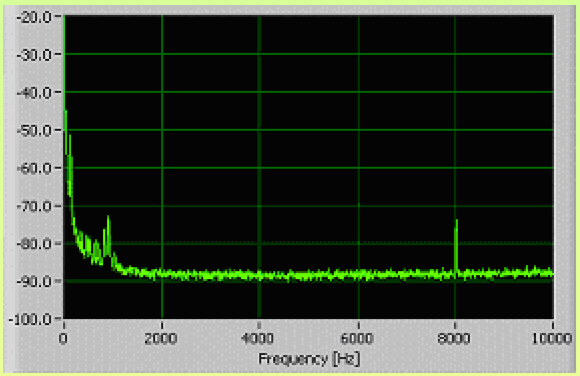
$$\frac{?\phi_{MZI}}{?\lambda_{FL}} = \frac{-2\pi n_e L_{MZI}}{\lambda_{FL}^{2}}$$

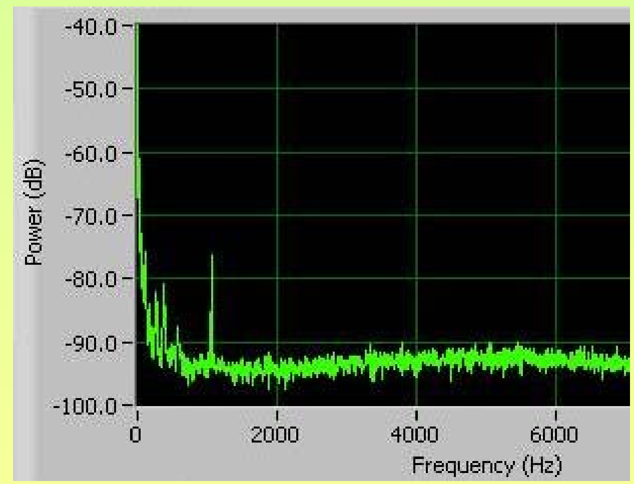
Used both MZI and MI to convert wavelength shift to phase shift.
Used small path difference (10m) used for simplicity

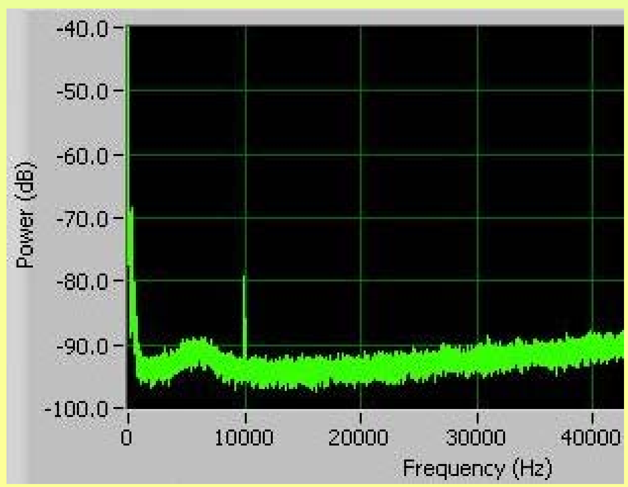
DFB Fibre Laser Hydrophone



DFB Fibre Laser Hydrophone

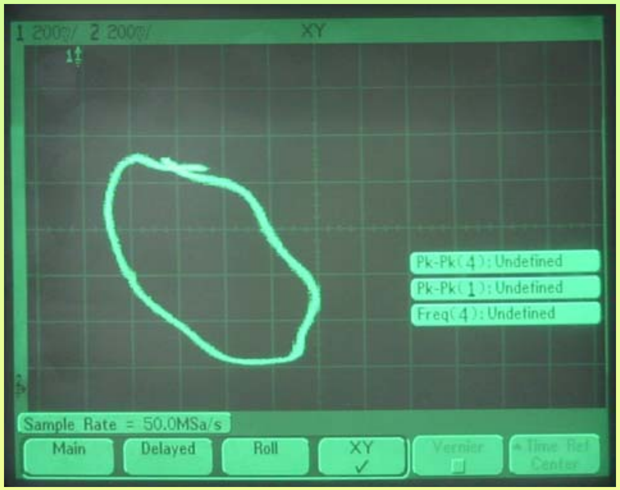


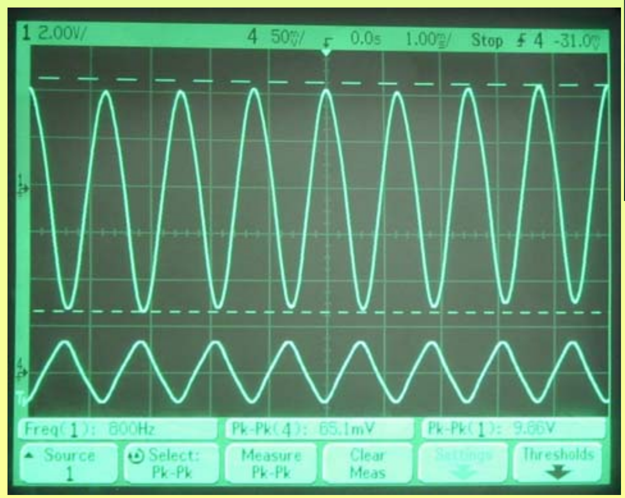


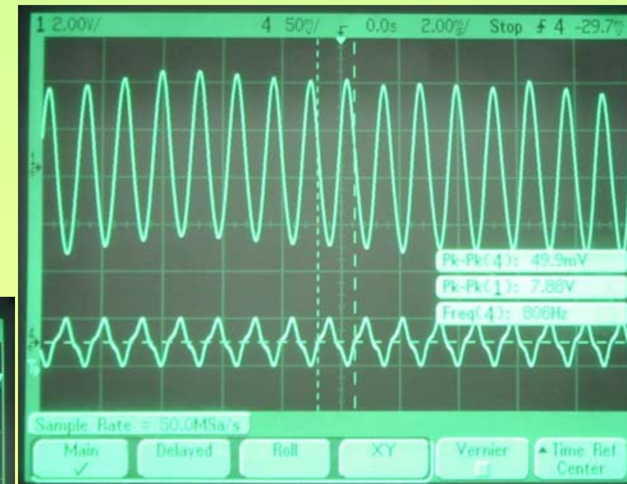


Steel water tank + calibrated ceramic hydrophone + digital demodulation (Sydney)

DFB Fibre Laser Hydrophone

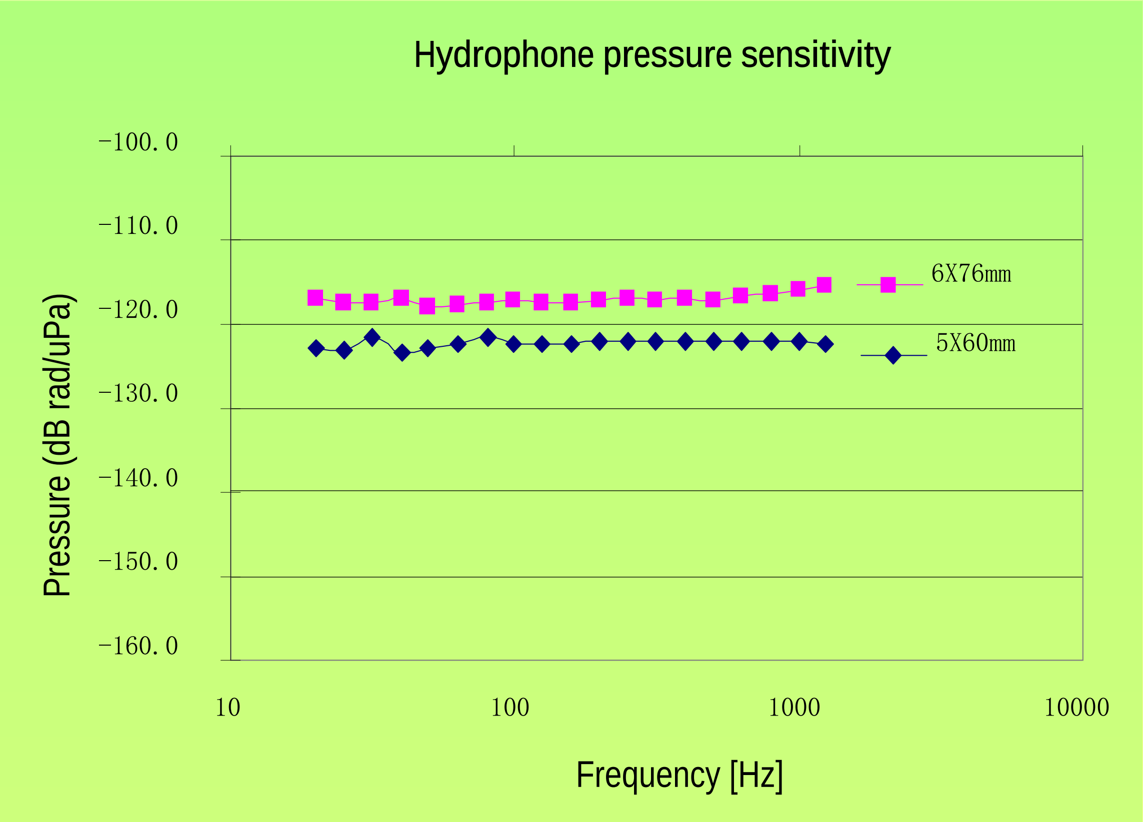






Vibration stage and accellerator + analog demodulation (Shanghai)

DFB Fibre Laser Hydrophone



Pressure sensitivity results of fibre laser hydrophones with two different packaging designs.

Conclusion

Fibre laser based hydrophone

Very high sensitivity **(<1000μPa/?Hz @1kHz)**

Very compact and small size **(ϕ5mm?60mm)**

Good frequency response (with equalisation)

High dynamic range

Dense multiplexing potential

Simple fabrication and low cost

High performance - thin hydrophone lines