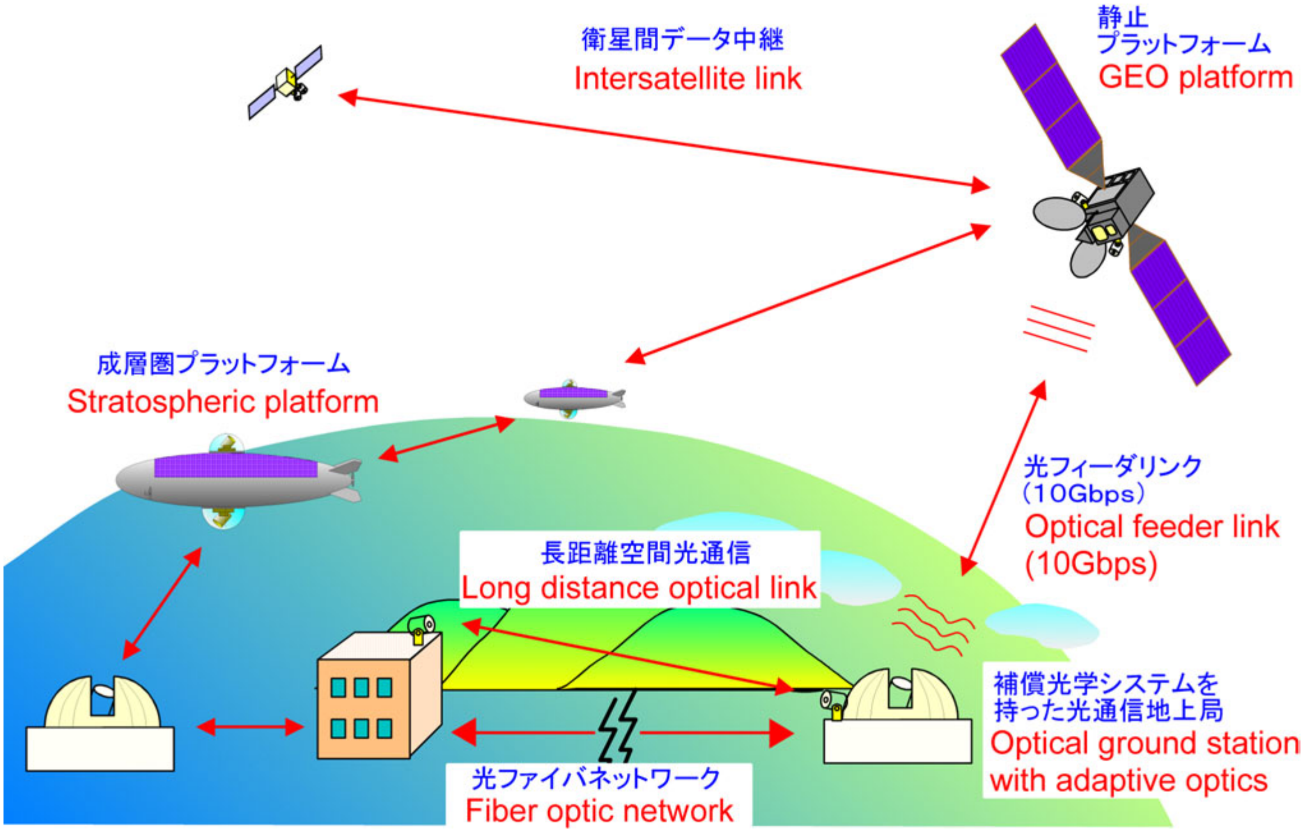
Fiber Optics in Space Missions: the experience from Japan

Yoshinori Arimoto
arimoto@nict.go.jp

Optical Space Communications Group
Wireless Communications Department

National Institute of Information and Communications Technology, JAPAN

Recent activities and future target missions of space laser communications in NICT



- Based on the proposal of a multi-gigabit optical feeder link, the Laser Communications Demonstration Experiment (LCDE) was planned as an initial capability experiment at the International Space Station, Japanese Experimental Module and its definition study and basic design was performed from 1997 to 2002.
- Analog optical feeder link experiment was planned for the test flight of a stratospheric platform in 2003.

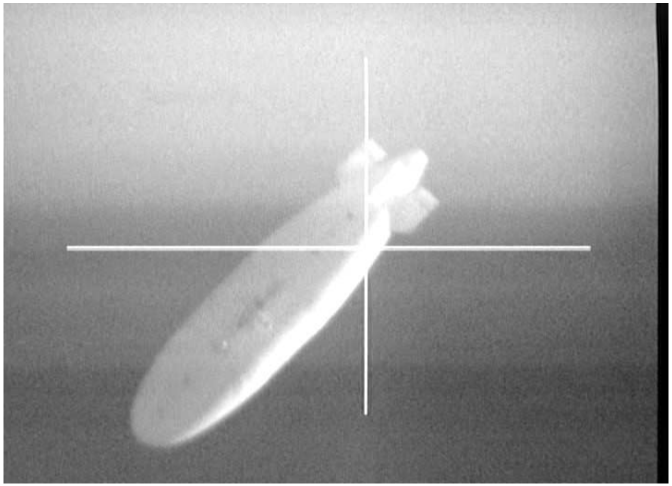
Recent demonstration experiments

Acquisition and tracking experiment in airship test flight

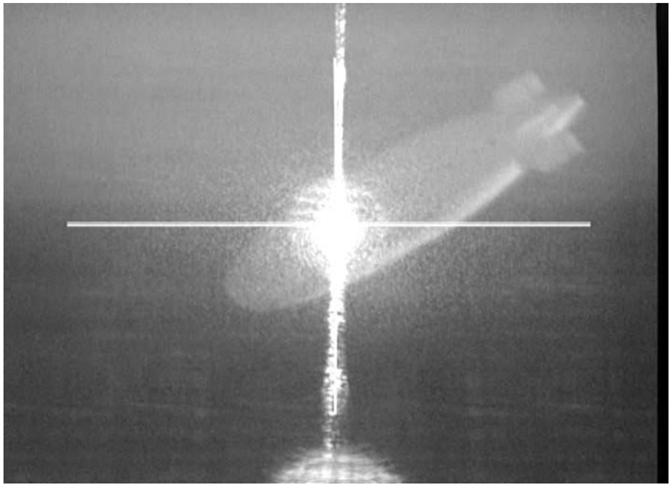
- Development program was started in 2003. Experiment was performed November 22nd, 2004.
- Ground terminal is tracking to the airship at 4-km altitude.
- Because the flight time was limited to two hours, we only demonstrate acquisition and coarse tracking provided by a gimbaled telescope with a CCD camera.
- Original mission objective was to transmit a digital TV broadcasting signal using 1550-nm optical link.

Beacon tracking experiment

Before beacon acquisition

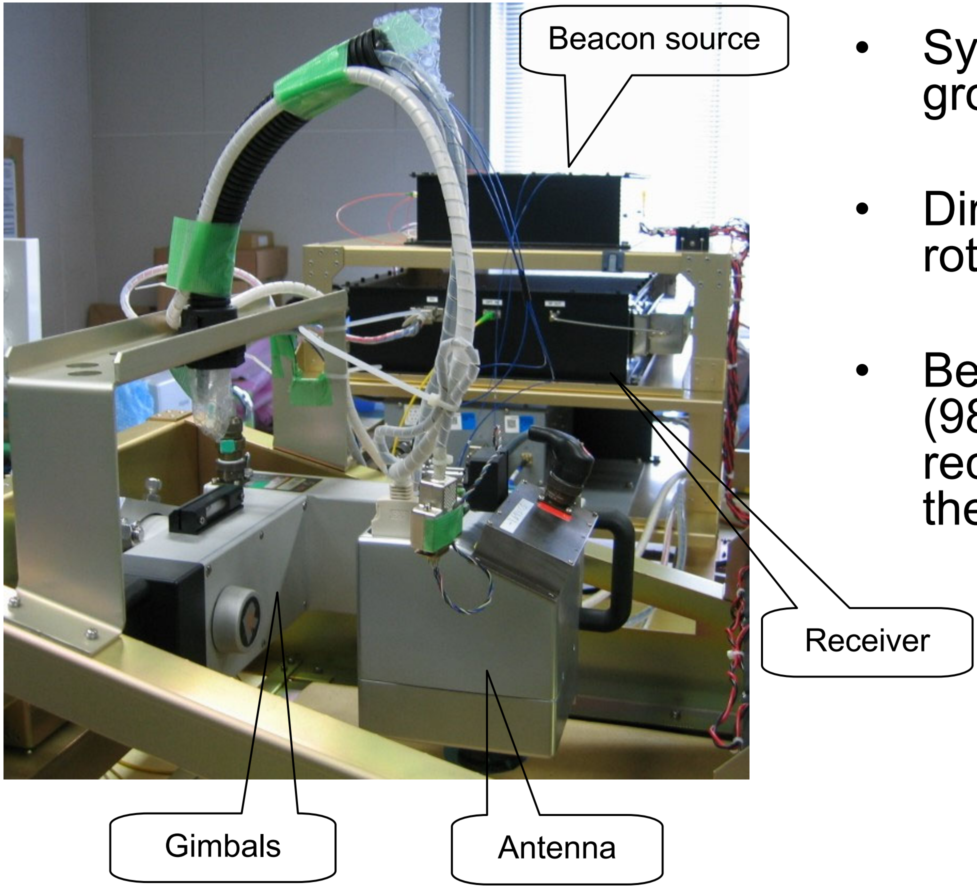


After beacon acquisition



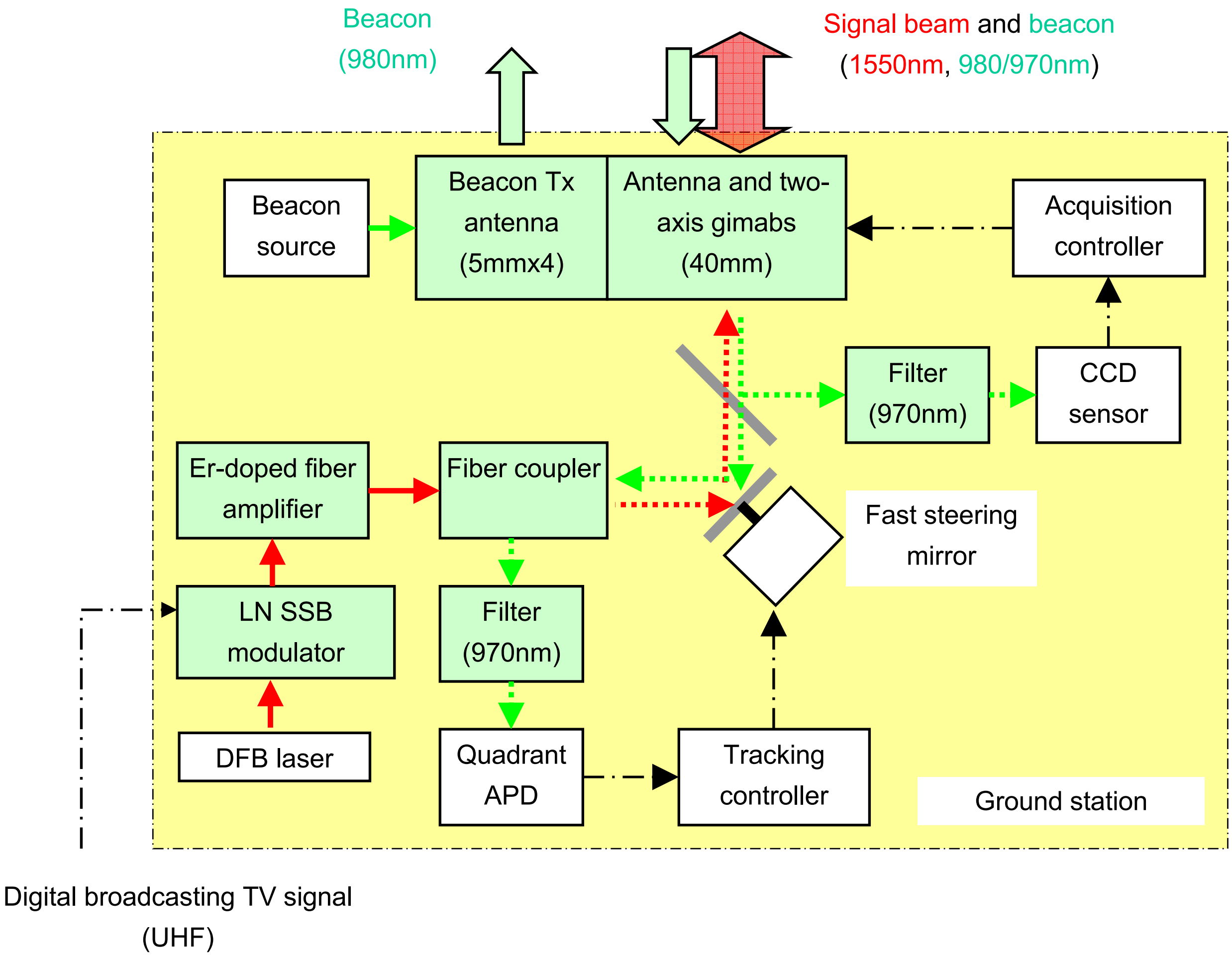
- Bi-directional acquisition and tracking at both onboard and ground laser communication terminals has been successfully performed. Two-axis gimbals are controlled based on the centroid of the CCD sensor shown as cross cursor.
- Tracking error (error between predicted pointing angle and real tracking angle) was less than 0.5 degrees.

Onboard laser communication terminal

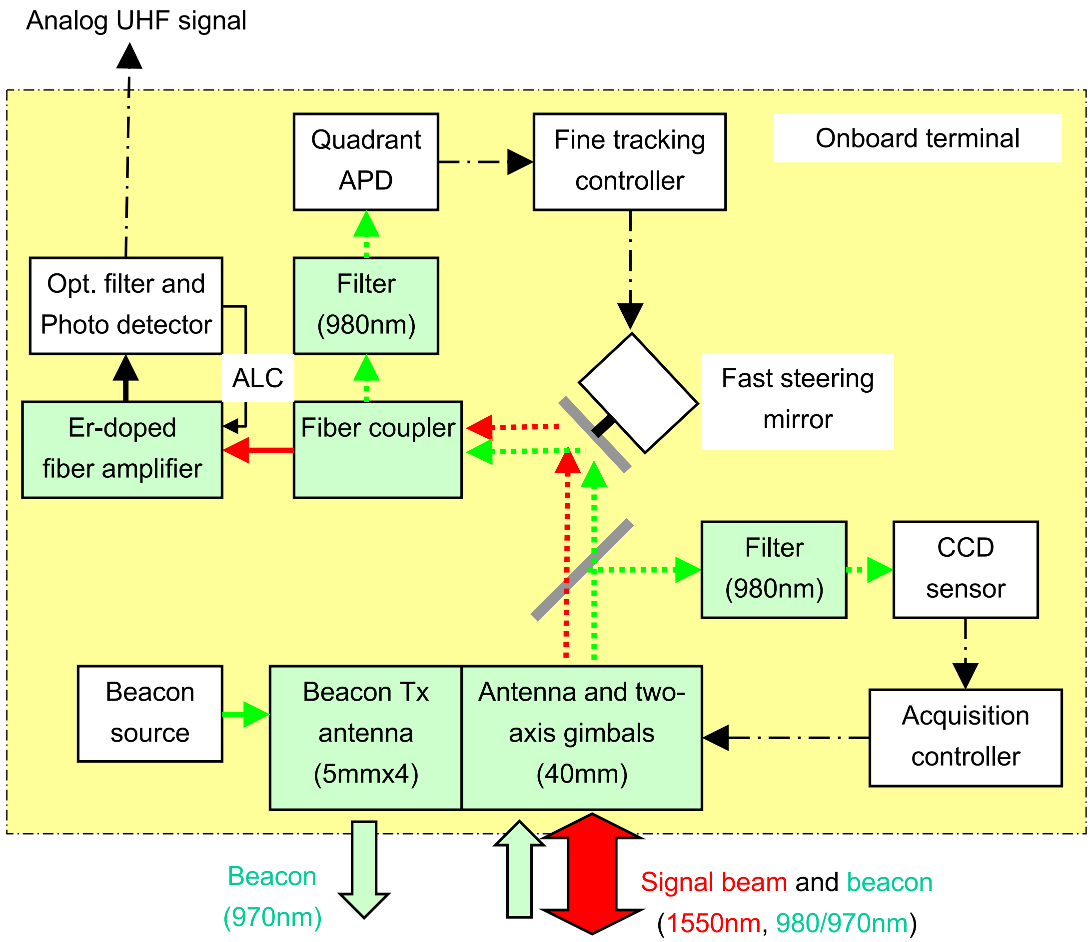


- System is identical with the ground terminal
- Direction of gimbals is rotated by 90 degrees
- Beacon laser source (980nm) and optical receiver installed aside of the optical antenna module

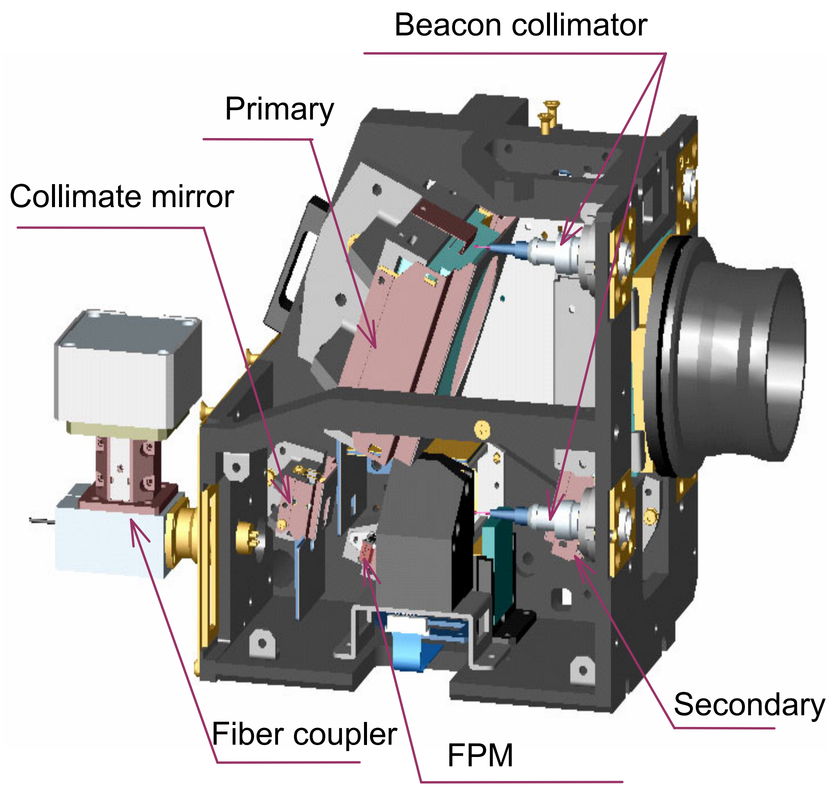
Configuration of ground terminal



Configuration of onboard terminal



Antenna module and two-axis gimbals

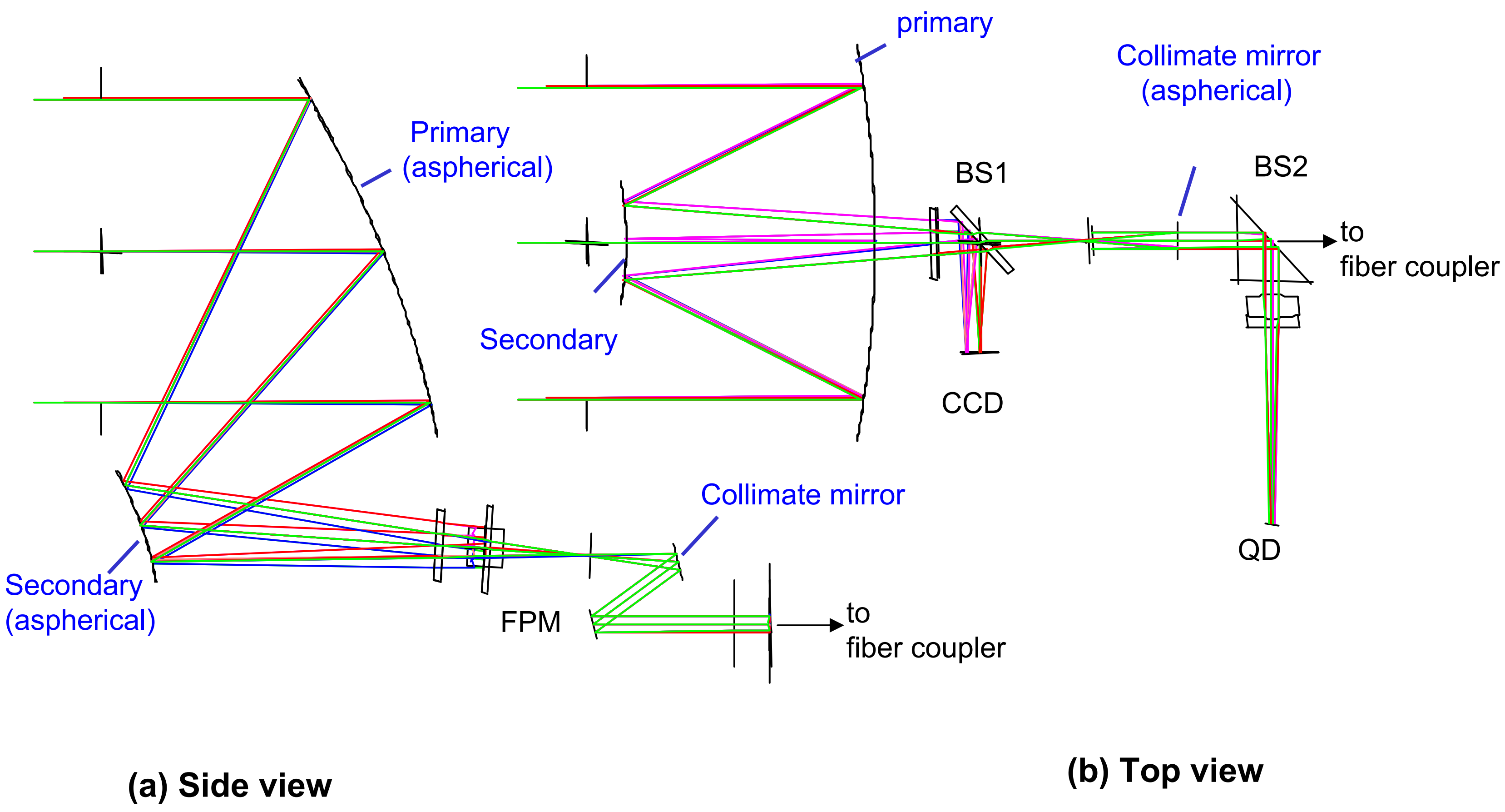


Internal layout of antenna module

External view of antenna module and two-axis gimbals

- Three plastic off-axis aspherical mirror are used to realize compact and light weight optics. Effective antenna aperture is 4 cm.
- Antenna module weight: 2.4kg, Gimbals weight: 9kg.

Design of off-axis aspherical mirror



Primary specification

Link distance:	200 m (min.), 4.6 km (max.)
Elevation angle:	more than 53 degrees (acquisition), more than 60 degrees (communication)
Laser wavelength:	1.562 μm (uplink communication) 0.98 μm (uplink beacon), 0.97μm (downlink beacon)
Output power:	within class 3A (safe without optical instrument)
Antenna size:	4cm in diameter (1.5 μm TX/RX), 0.5cm in diameter x 4(0.98μm beacon TX)
Gimbal angle:	+/- 45 degrees (Az), +/- 45 degrees (El), through window
Gimbal performance:	speed: 2 degrees/sec, accuracy: 0.01degree
Acquisition FOV:	0.9 degrees (diagonal), using Si-CCD
Beacon beam width:	2 degrees (uplink), 0.5 degrees (down link)
Weight:	less than 26 kg including antenna, acquisition tracking system and receiver
Power consumption:	less than 70 W
Number of flight:	2 (days, expected)
Link procedure:	maintain beacon tracking from the initial ascent till the height is bellow 200 m. try to make a communication link if the elevation angle is more than 60 deg.
Data processing:	predict the pointing angle for both onboard and ground terminals based on the online telemetry data for an initial acquisition and re-acquisition.

Link budget

Optical feeder link

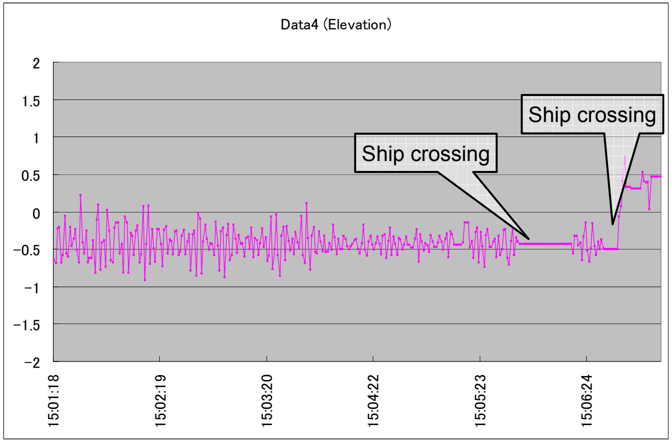
Wavelength:	1552nm
Output power:	100mW (+20dBm)
Antenna diameter:	40mm
Beam divergence:	49.4μradian
Link distance:	4.6km
Elevation angle:	60degrees
Rx beam diameter:	24.6cm
Free-space loss:	-15.8dB
Turbulence loss:	-4.4dB (unavailability 10^{-9}, Tracking error: 5μrad.)
Inner optics loss:	-6.8dB
Receiving power:	-7.0dBm
Min. required power:	-24.0dBm (C/N>40dB)
Link margin:	17.0dB

Beacon link

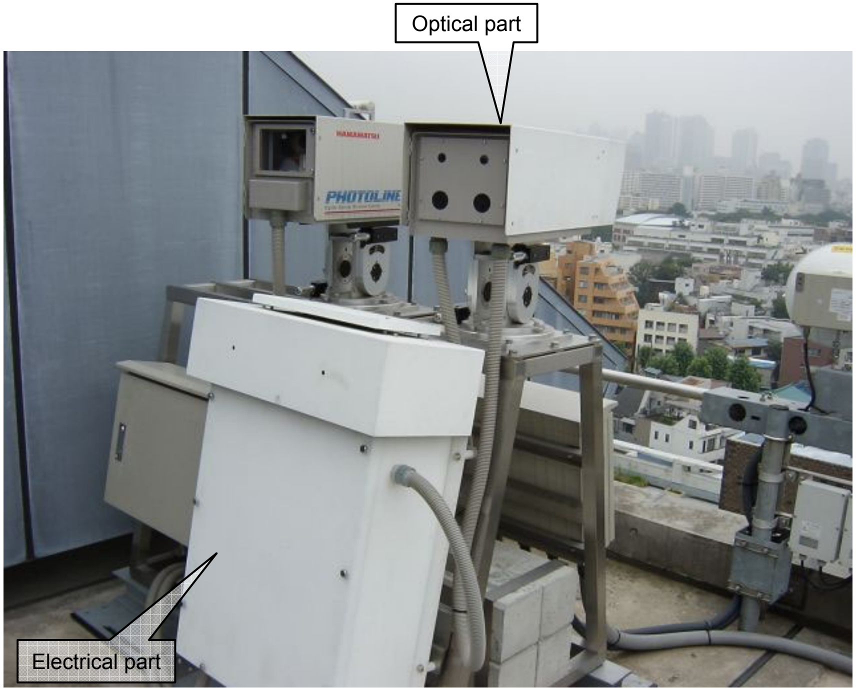
Wavelength:	980/970nm
Output power:	50mW (+17dBm)
Antenna diameter:	5mm
Beam divergence:	2degrees
Link distance:	4.6km
Elevation angle:	60degrees
Rx beam diameter:	159m
Free-space loss:	-72.0dB (40mm diameter)
Turbulence loss:	-3.9dB (unavailability10^{-9})
Receiving power:	-58.9dBm
Min. required power:	-79.6dBm (CCD), -60.0dBm (Quad. APD) (at the antenna aperture)
Link margin:	20.7dB(CCD)/1.1dB(APD)

(Test flight of the airship was to be performed under the clear sky condition because the pilot should control the airship from the ground using TT&C link.)

Ground demonstration experiment



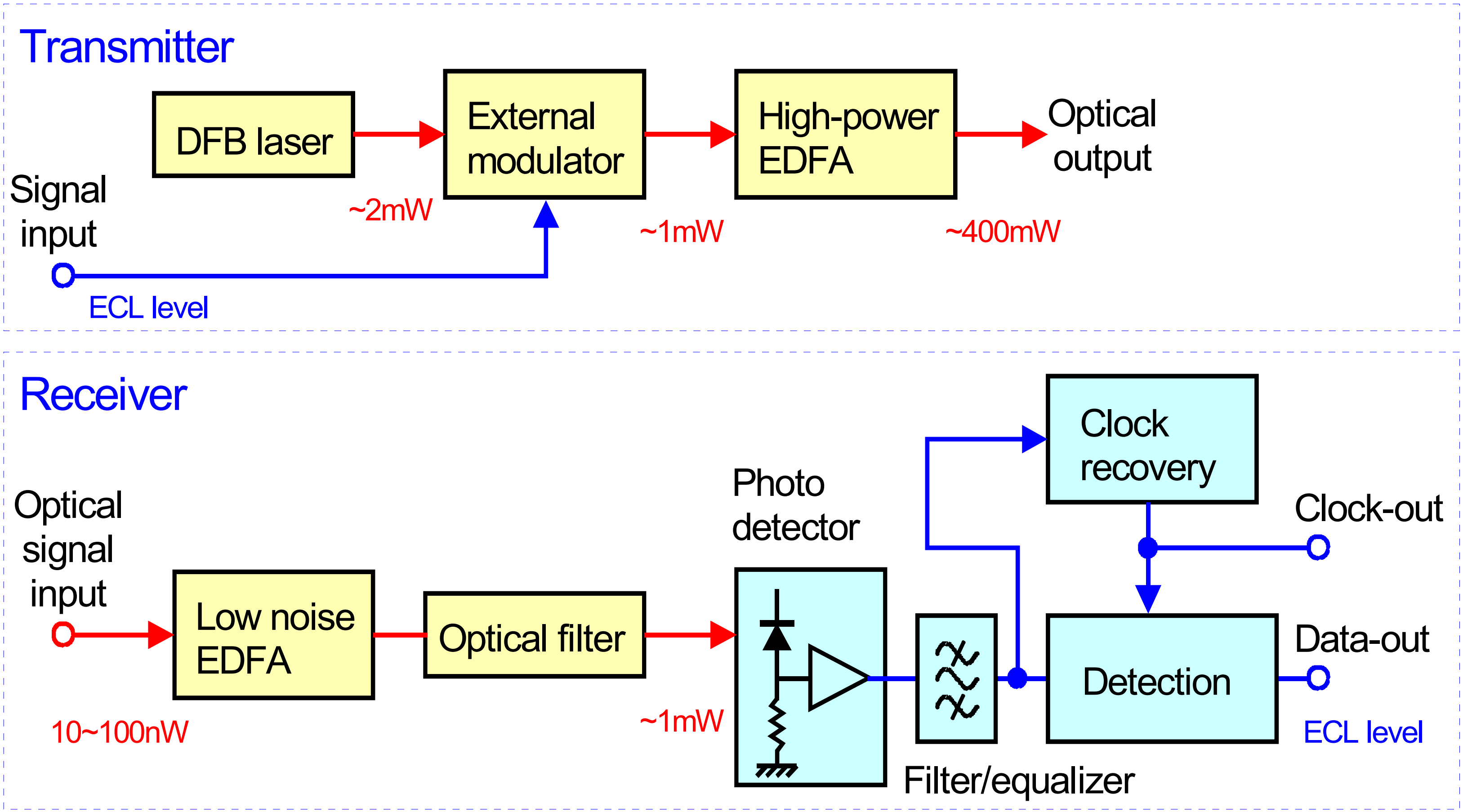
Tracking error history at the ship to coast optical link experiment.



First fiber-to-fiber stable optical link was demonstrated in Waseda University campus at 1-km link distance.

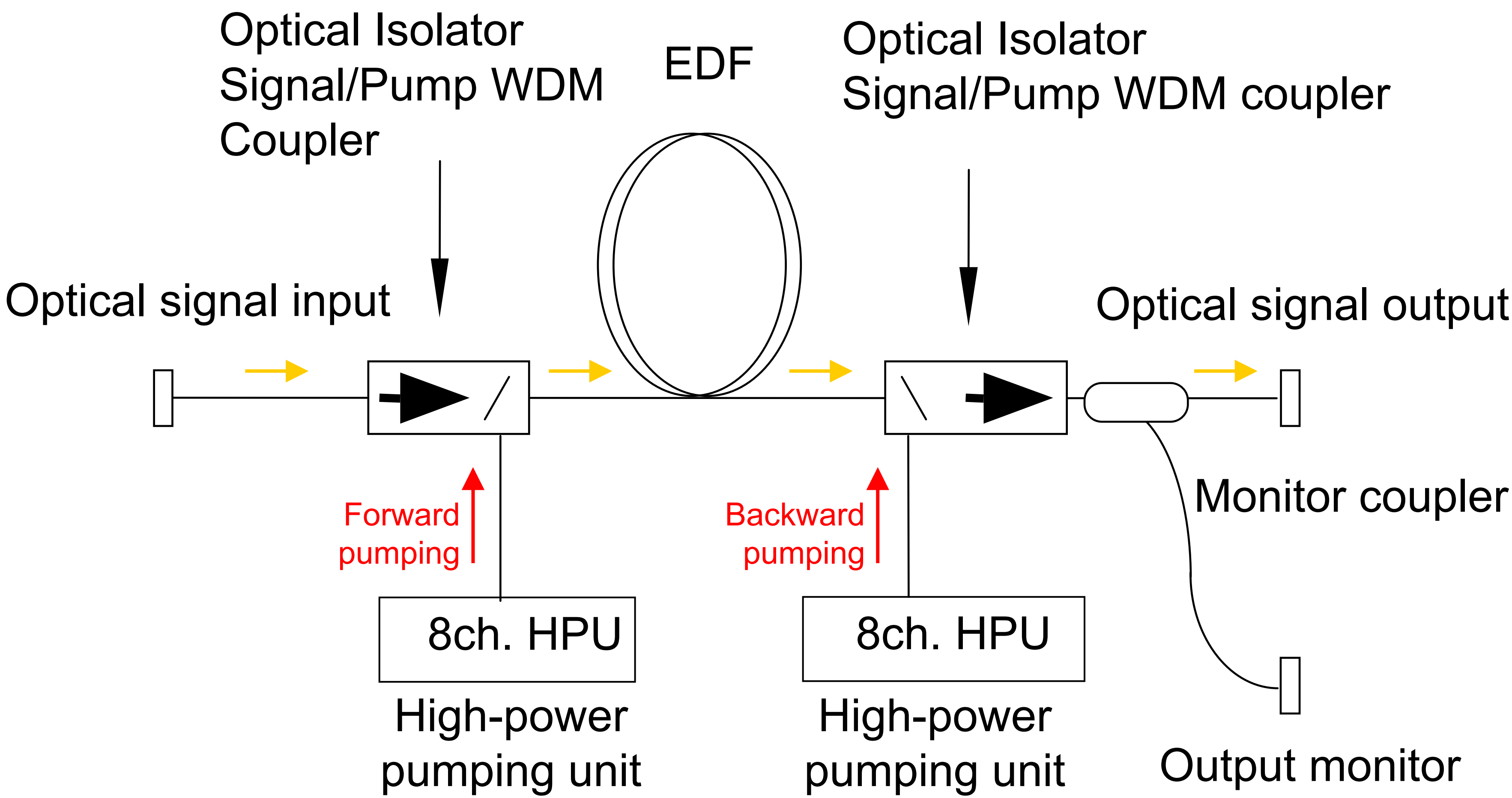
Fiber optic key components for space laser communication

Optical transceiver application

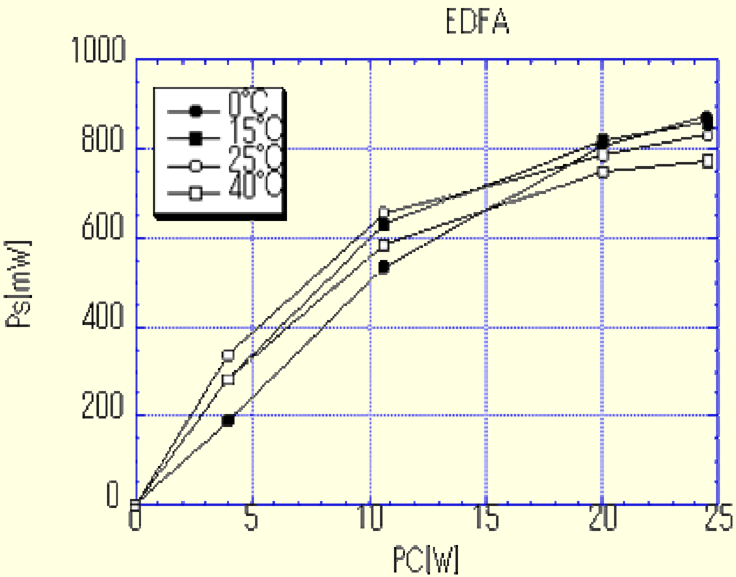


High performance (good sensitivity and power efficiency) optical transceiver will be realized using Er-doped fiber amplifiers. But, we need to focus received signal beam stably onto a single mode fiber aperture.

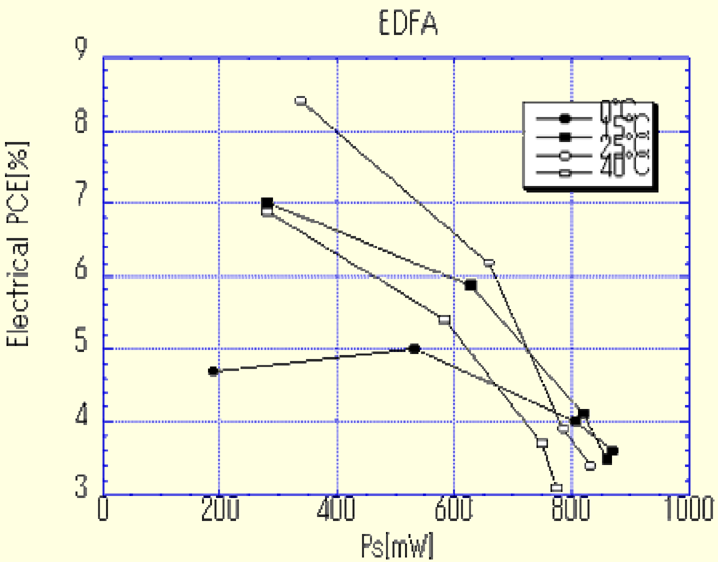
Configuration of high-power EDFA



High power EDFA
- Power efficiency improvement -



Relationship between the power consumption and EDFA output power

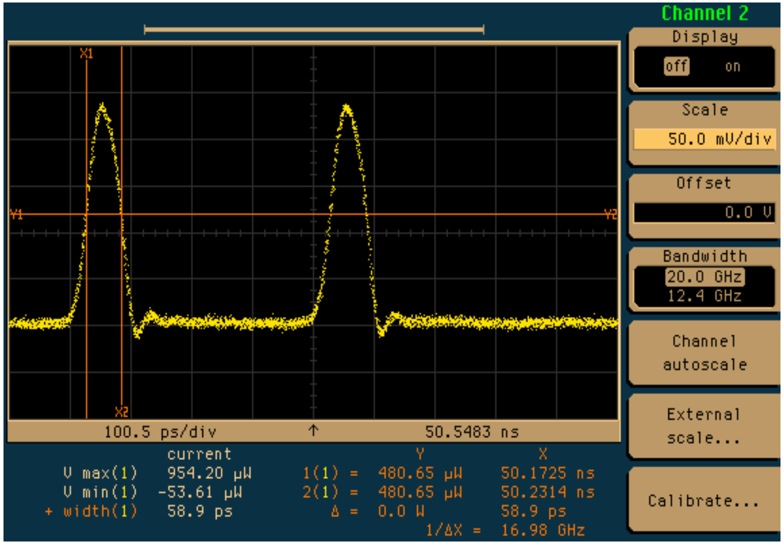


Relationship between the power consumption efficiency and EDFA output power

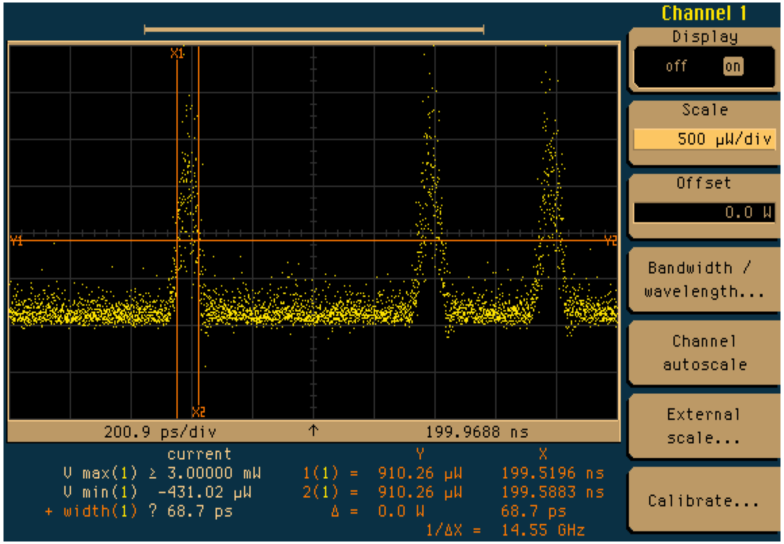
Using cooler less pumping laser (FBG wavelength stabilized), an 8% wall plug efficiency had been achieved.

Improvement of the efficiency in driving circuit will be required (PWM, switching regulator, serial connection of pumping LDs).

Short pulse signaling of 1550-nm laser

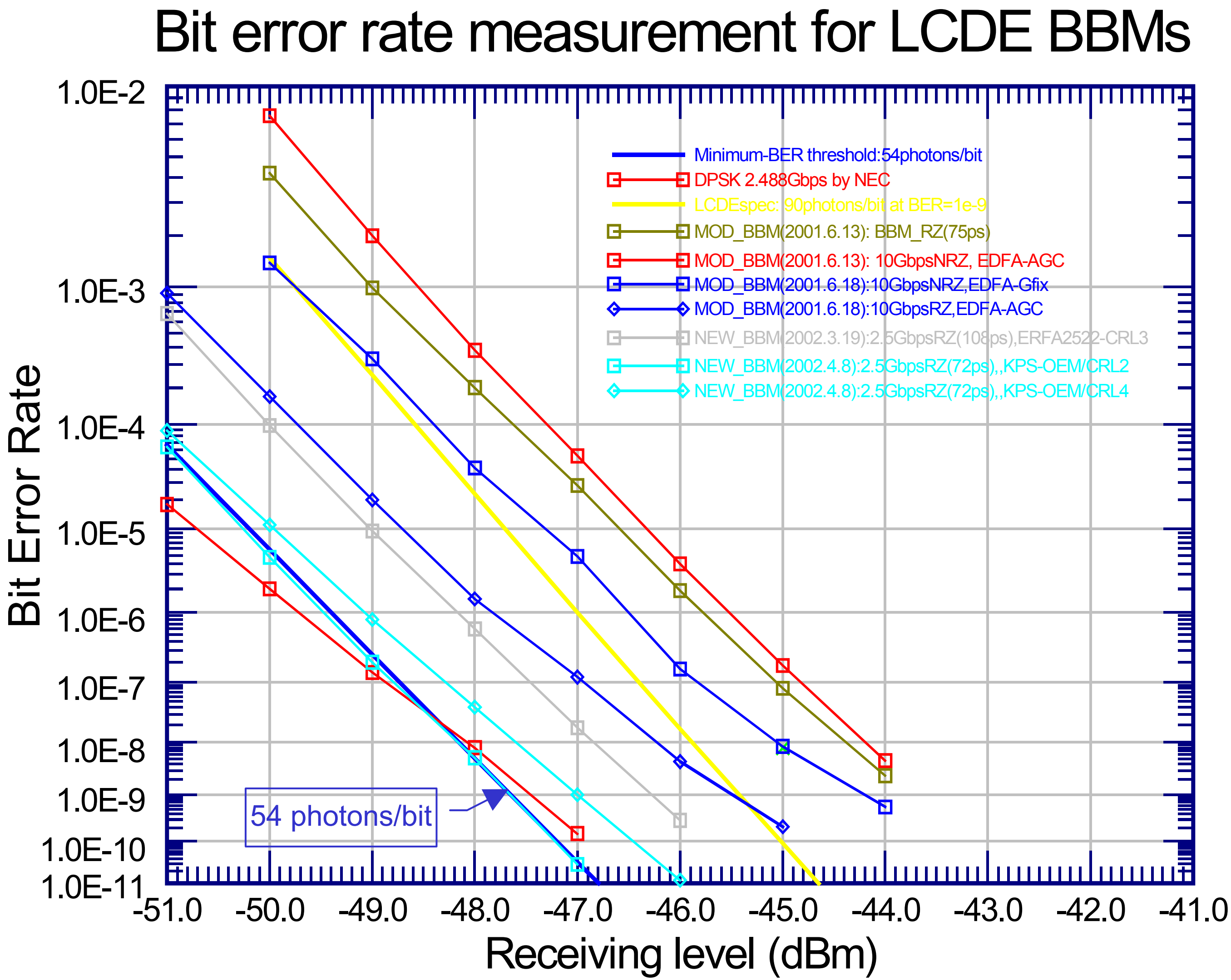


Optical signal before the high-power EDFA. Transmitting 2^7-1 PN sequence with the data rate of 2.5 Gbps. LN external modulator is used.

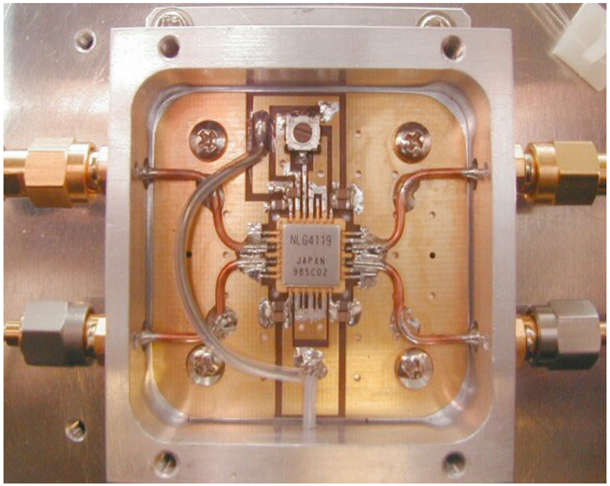


Optical signal after the Low-noise EDFA. ASE (amplified spontaneous emission) increases shot noise, but, there is no waveform distortion.

Transceiver performance improvements

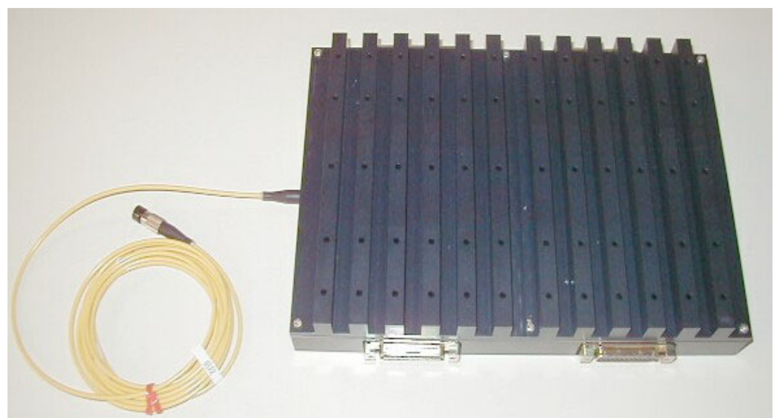


Components used for optical transceiver



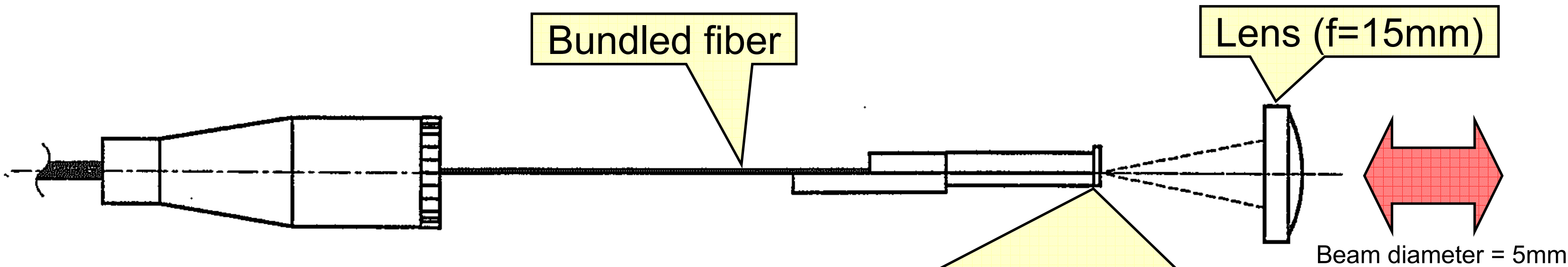
Short RZ-pulse generator using a 20Gbps GaAs logic IC

Gain unit for high power Er-doped fiber amplifier

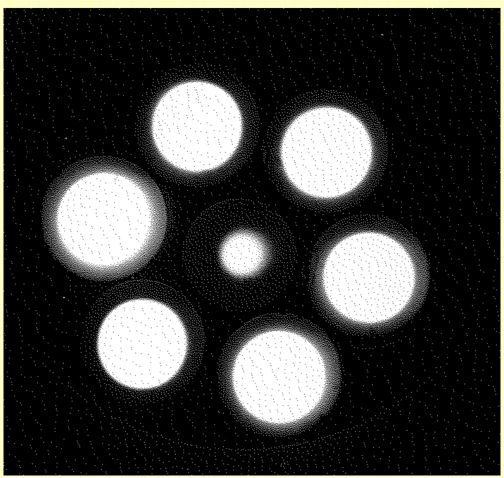


Pumping unit (1/2) for high power EDFA. 8-fold laser output at 1480 wavelength are combined by AWG to a 800mW pumping signal.

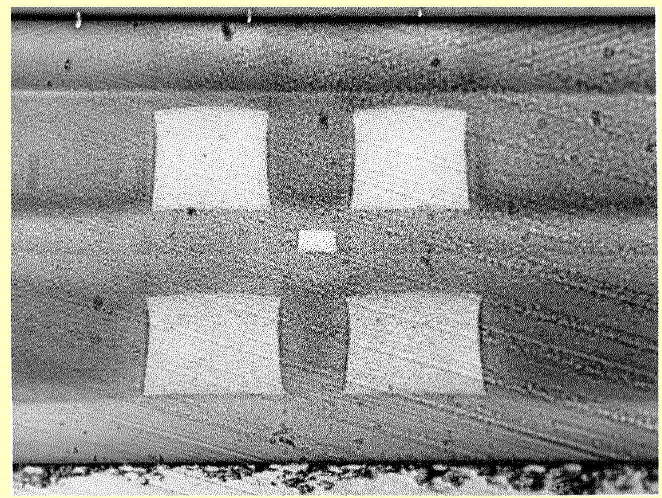
Bundled fiber coupler trial fabrication



Input/output aperture (Lens side)

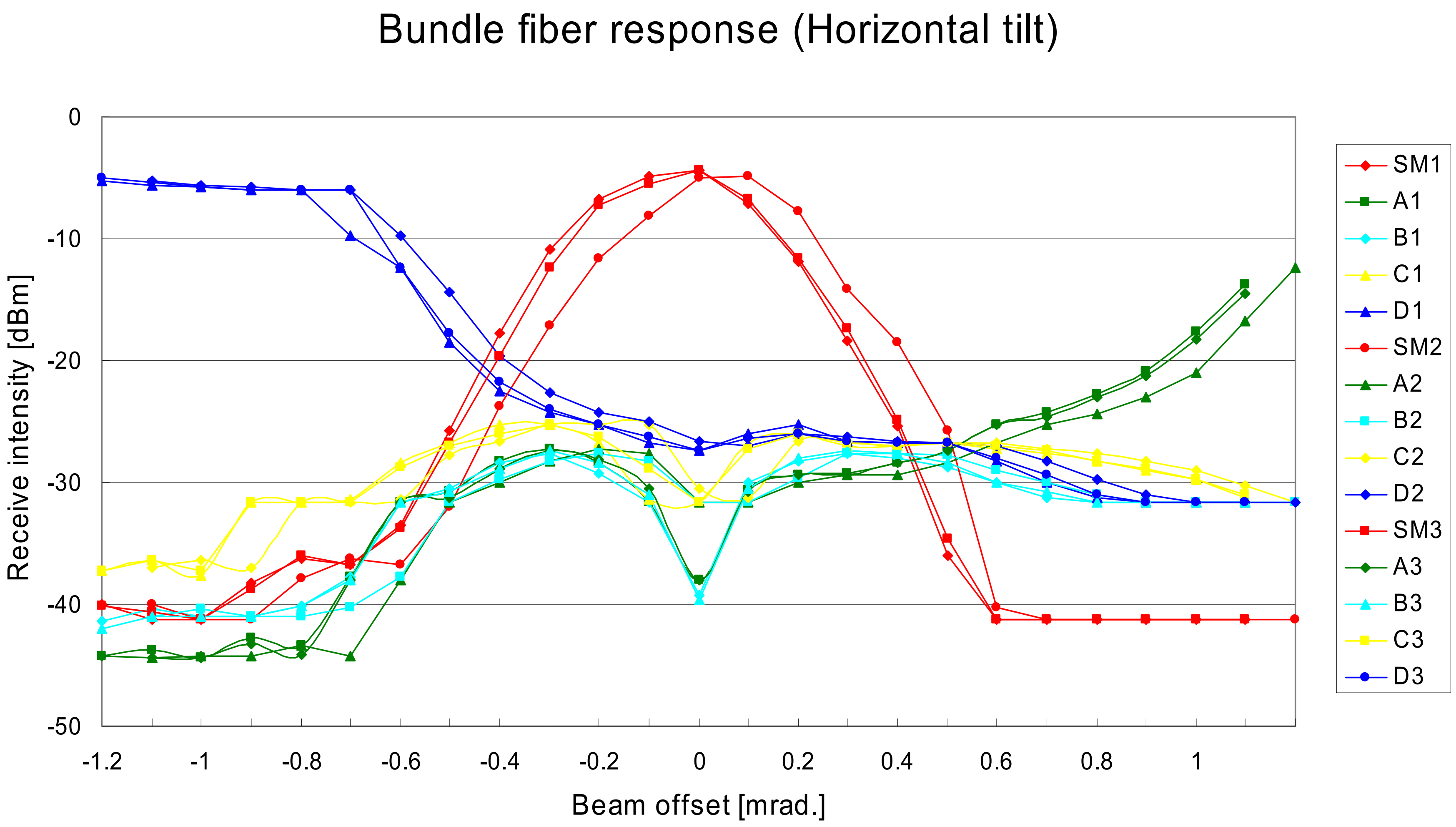


Bundled fiber (SM:1, MM:6)

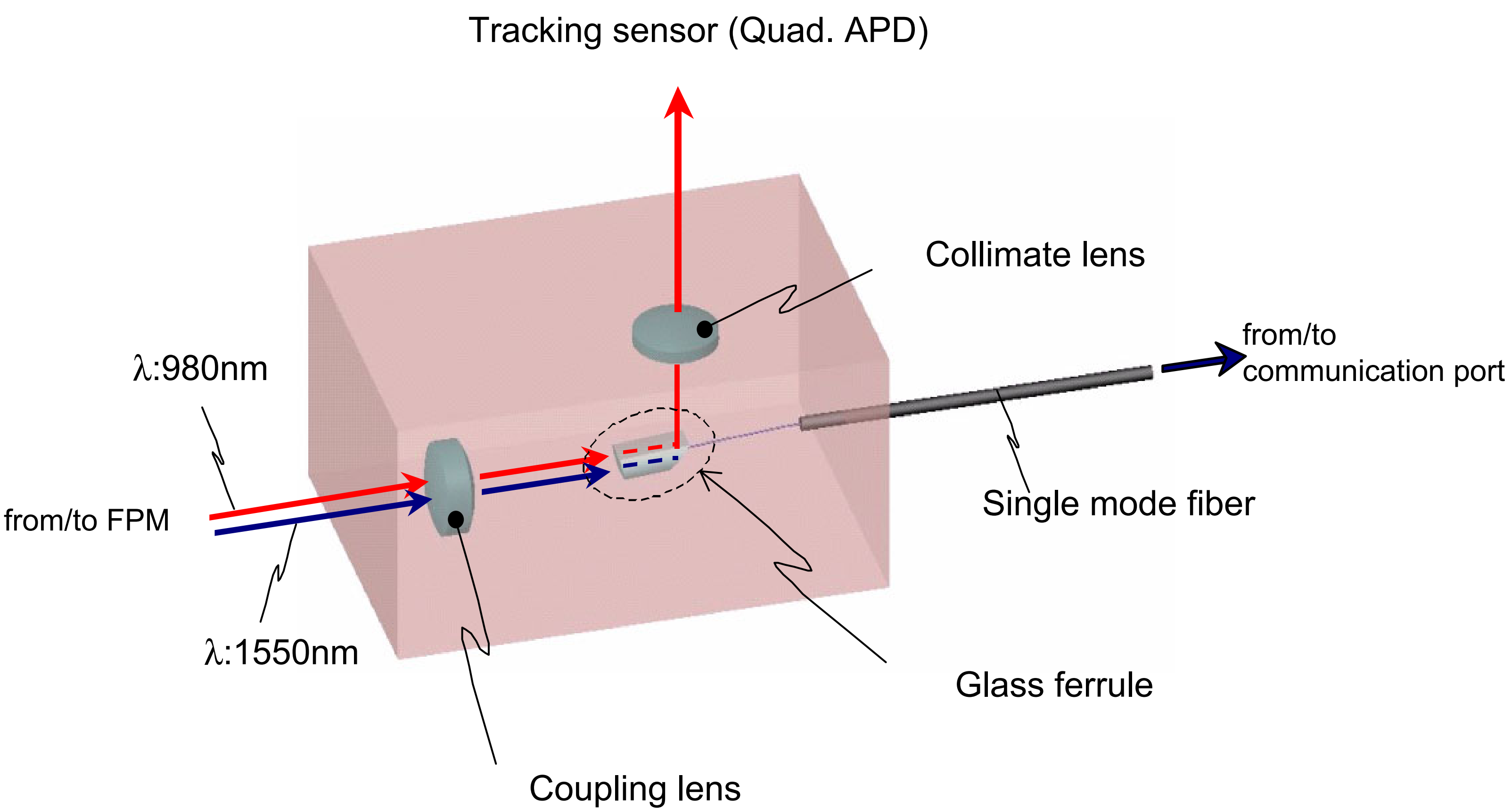


PLC fabrication (SM:1, MM:4)

Performance of bundled fiber coupler

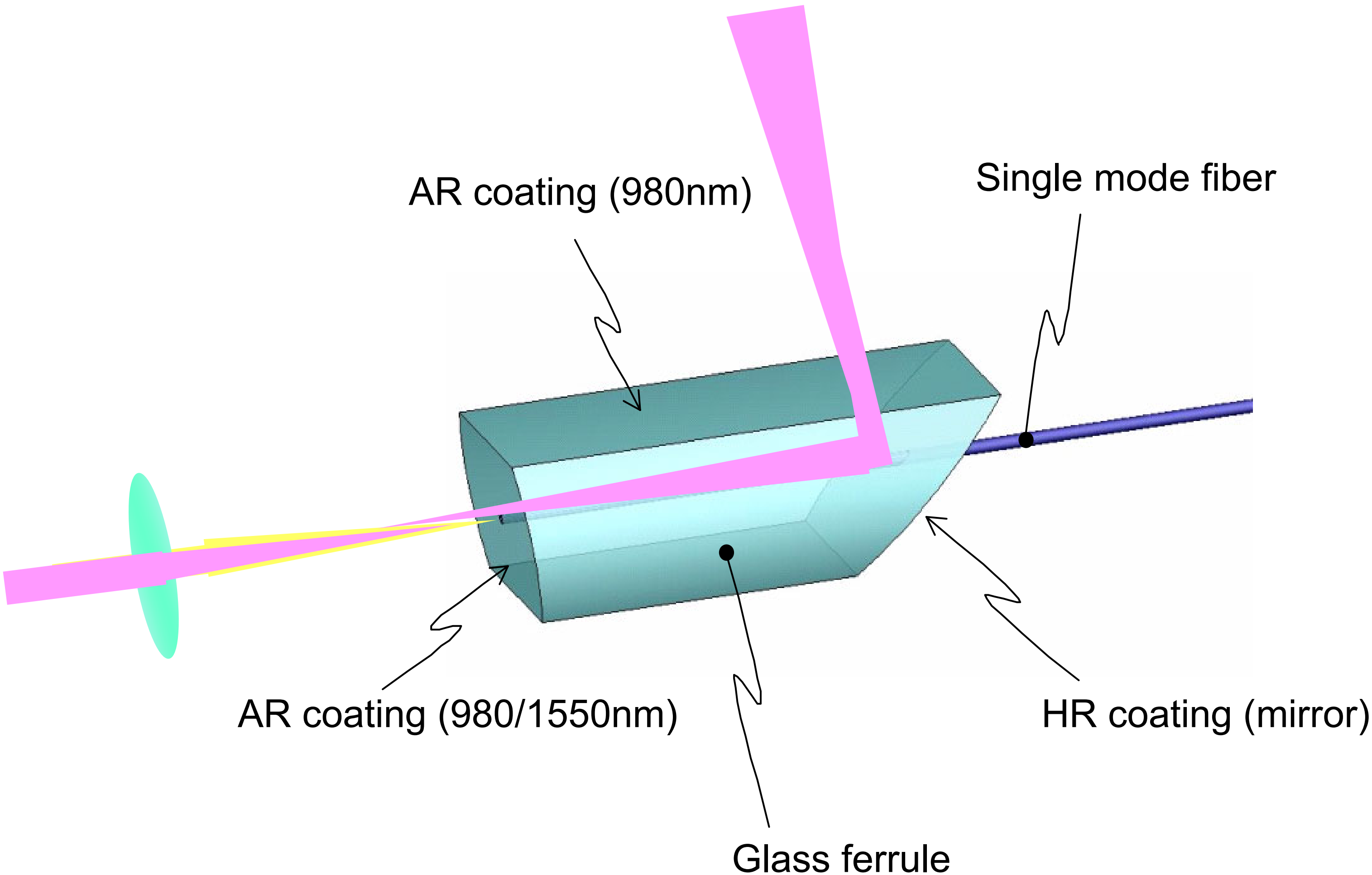


Configuration of integrated fiber coupler

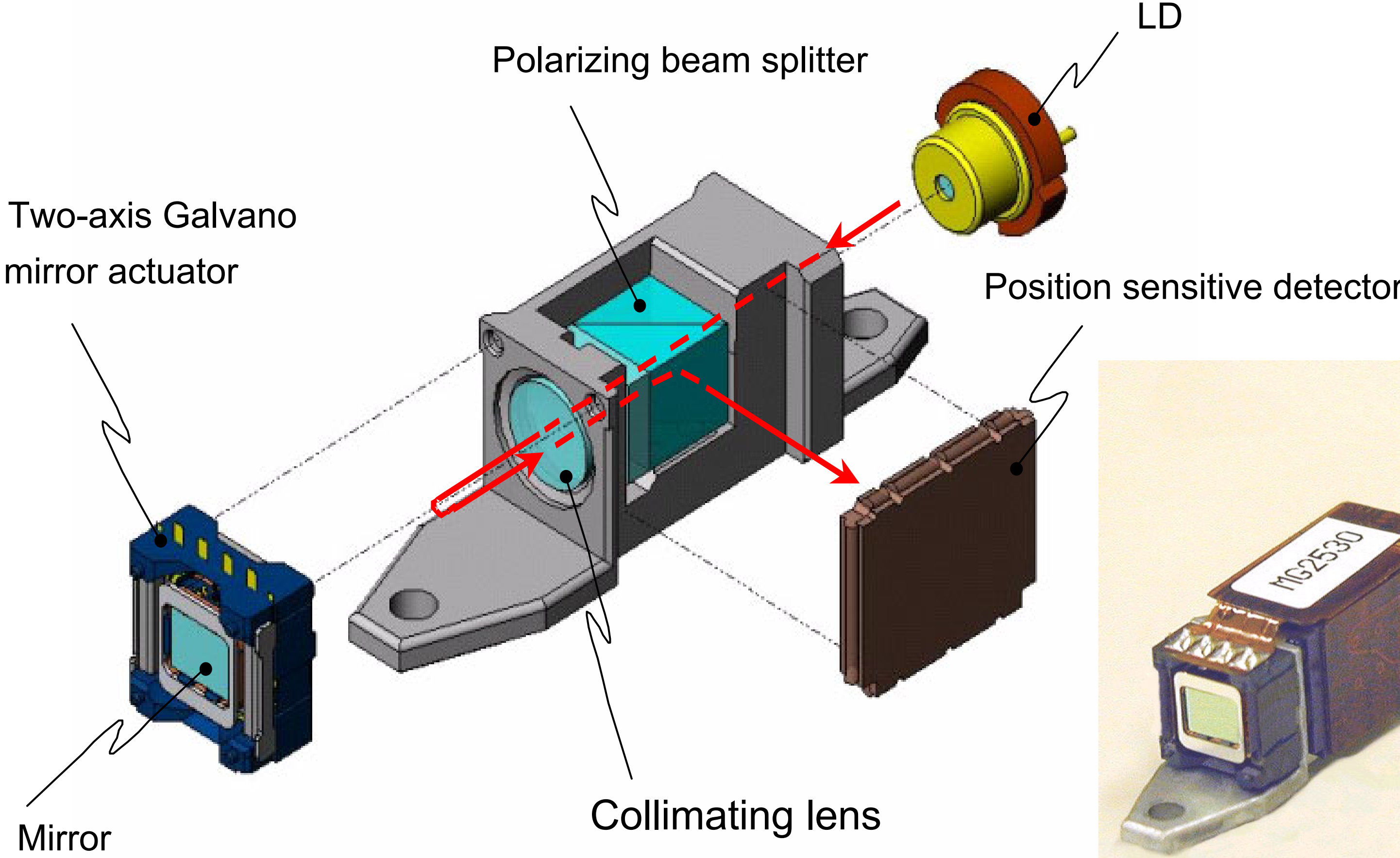


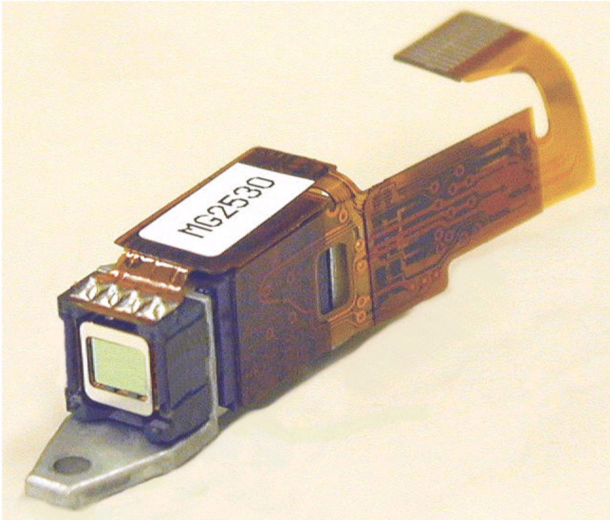
Beam at 980-nm wavelength is separated after the 1550-nm beam is coupled to single mode fiber.

Principle of integrated fiber coupler



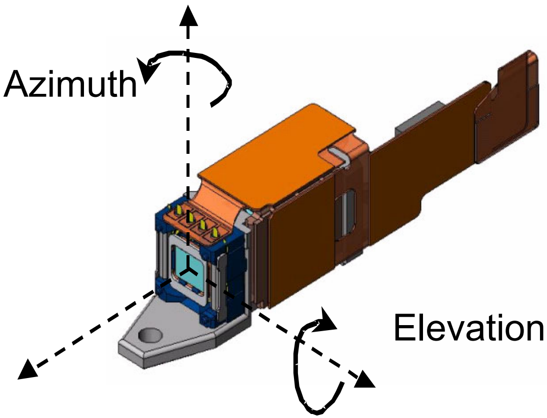
Miniature fast steering mirror (FSM)



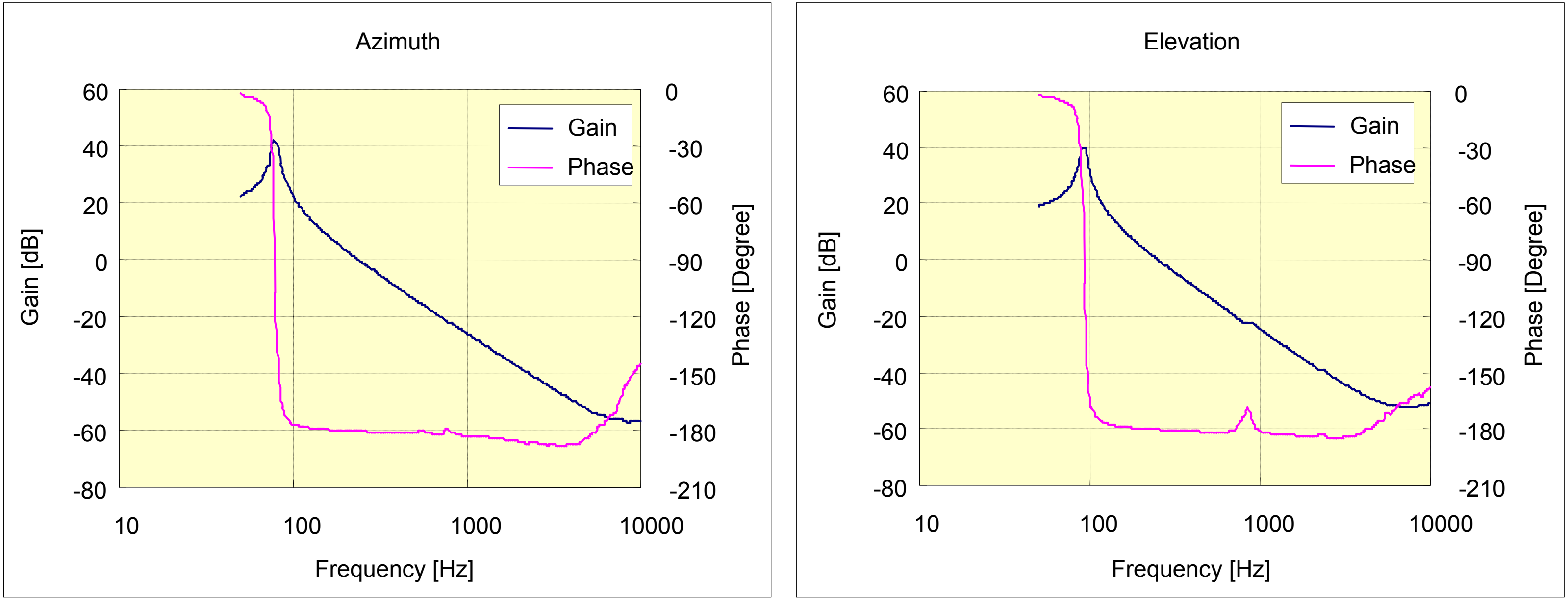


FSM frequency response

Measurement result with a PID position servo system

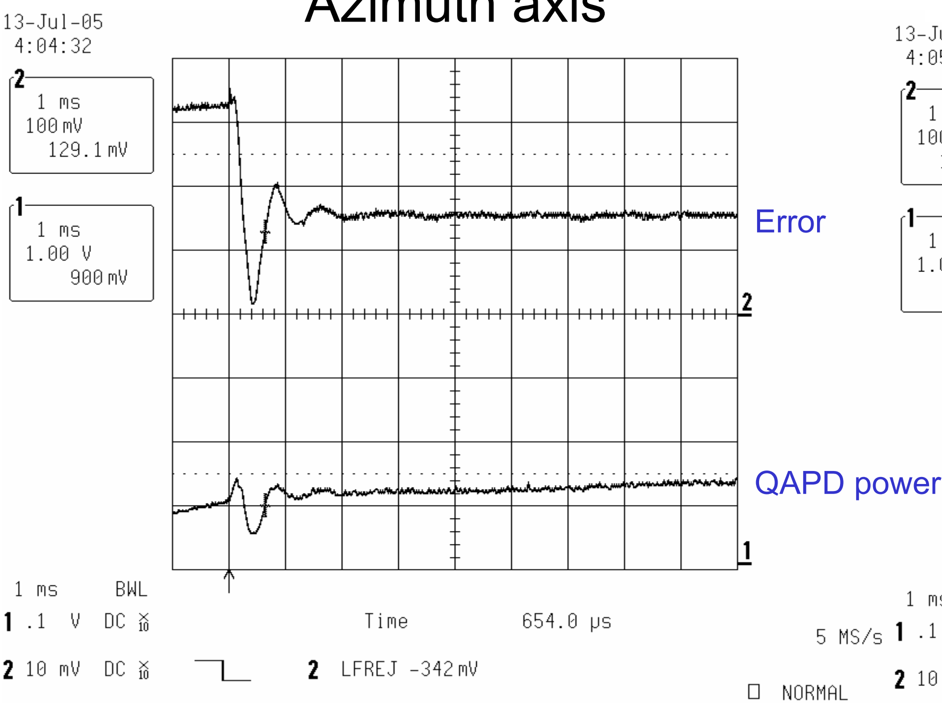


(Gain/phase response of miniature fast steering mirror)

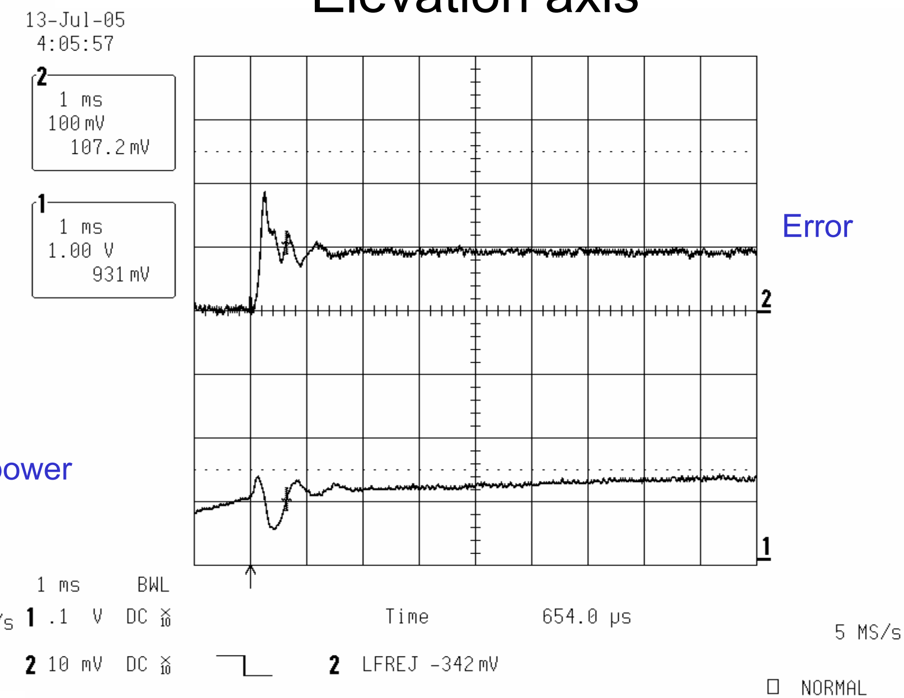


Acquisition performance of FSM/QAPD fine tracking mode

Azimuth axis



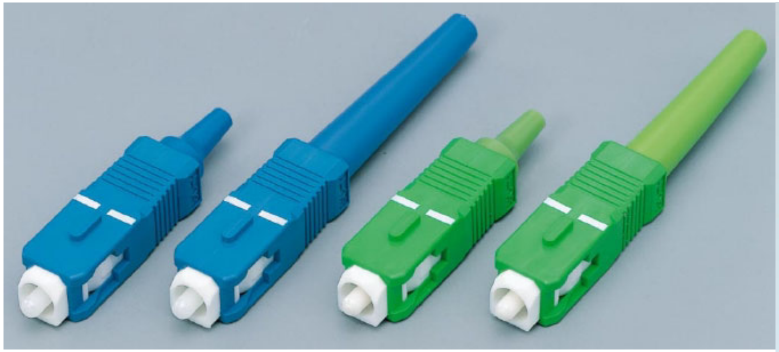
Elevation axis



Connection between fiber optic components

- Two types (SC/PC, FC/PC) of single mode fiber connector is normally used
  for 1550-nm components and pumping laser (980-nm).
- In some cases, connection between FC/APC is unstable.
- Key width of FC/APC housing should be matched.
  N-type(2.14 +0/-0.005 mm), R-type(2.02 +0/-0.05 mm), PC(2.0 +/-0.15 mm)
- Curvature Radius of Ferrule face (FC/APC) should be matched.
- SC/(A)PC is more stable, but, could it be space qualified?

SC/(A)PC connector



FC/(A)PC connector

Photo from Seikou-Giken

Conclusion

- New technologies/components were developed and evaluated at NICT to realize compact laser communication terminals for future space laser communication system.
- To couple free-space laser beam into single mode fiber is still difficult, but, tracker-integrated fiber coupler will be used in the near future.
- Fiber optics might be used for broadband (millimeter wave) satellite transponder based on Radio-On-Fiber technology for the future.
- Key components to build a fiber optic transceiver, such as LN external modulator, tunable optical filter are under evaluation at NICT.