Innovative Multi-Point Impregnation Sensors Based on Polymer Optical Waveguide Technology

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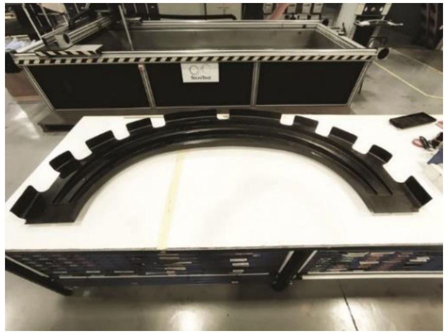
1. Background

- RTM enables precise moulding of large and complex components.
- Mitsubishi Heavy Industries (MHI) is actively developing advanced RTM technologies for high-performance composite manufacturing.

Frame [1)]



Rib [2)]
A. Abete

Spar [3)]
GKN Aerospace

Spoiler [4)]
Spirit AeroSystems

Footwell [5)]
KraussMaffei

Roof [6)]
Mubea

Monocoque Structural Cell [6)]
Mubea

1)https://www.compositesworld.com/articles/multi-flange-rtm-frames-enable-radical-rear-fuselage-design

2)https://www.compositimagazine.it/aeronautical-structural-rib-of-composite-material-with-rtm-techniques/

3)https://www.compositesworld.com/news/gkn-aerospace-commits-to-airbus-suswings-program

4)https://www.compositesworld.com/articles/high-rate-automated-aerospace-rtm-line-delivers-next-gen-spoilers

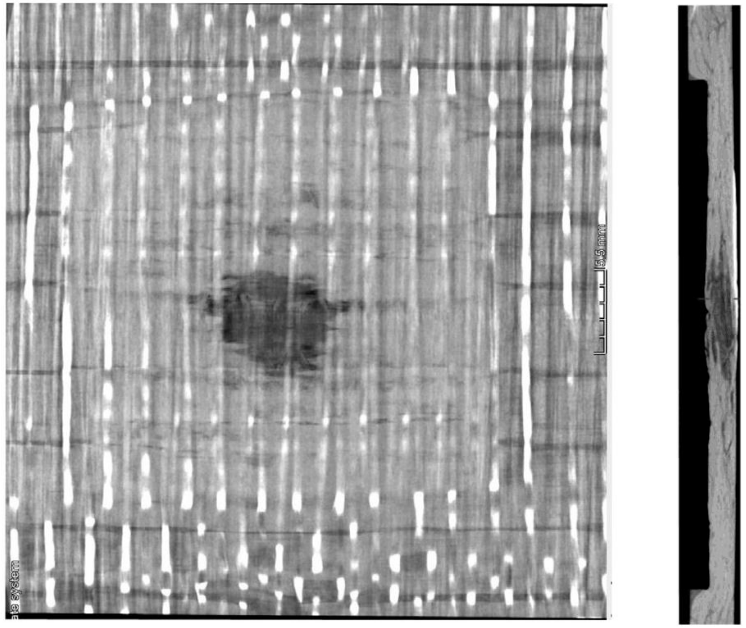
5)https://www.kraussmaffei.com/en/our-processes/resin-transfer-moulding-rtm

6)https://www.mubea.com/en/cfrp-structural-and-visual-parts

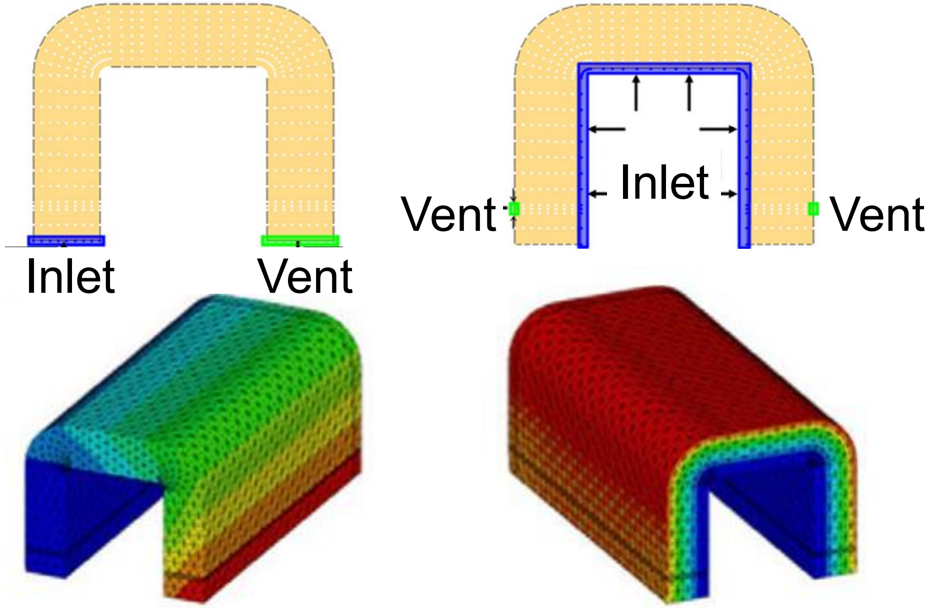
1. Background - RTM manufacturing requirements

- RTM manufacturing requires:
  - ✓ **High cycle** moulding
  - ✓ High quality **without resin starvation**
- Both are strongly influenced by the infusion strategy
- Achieving both simultaneously remains challenging

Example of resin starvation [7] (CT images)



Resin Flow Pattern Depends on Injection Strategy [8]



Resin Transfer Molding：RTM

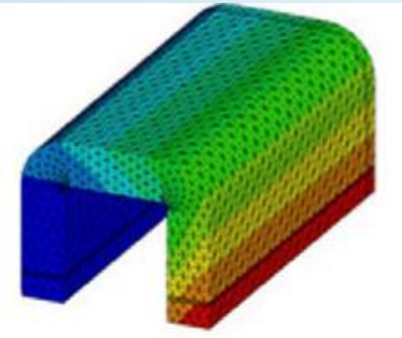
7) Susanne Nonn etc., Composites Part A 115 (2018) 57–65
8) Mitsubishi Heavy Industries Technical Review, Vol.48 No.4 (2011)

2. Objective

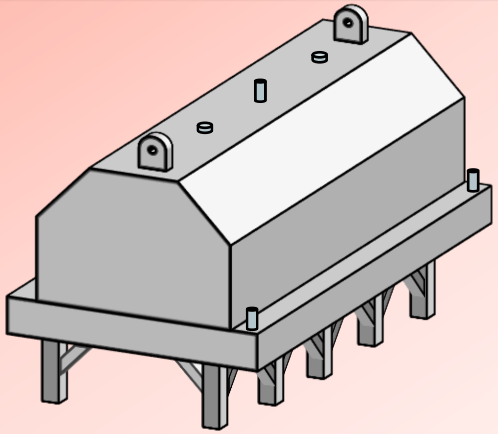
- Optimal infusion strategy design requires:
  - ✓ Accurate understanding of **resin flow behavior**
  - ✓ Validation of numerical simulation results
- However, in RTM processes:
  - ✓ The mould is closed → Resin flow cannot be directly observed
- **Objective**:

  Development of a multi-point resin flow sensor for in-situ monitoring in RTM

Simulation: Visible



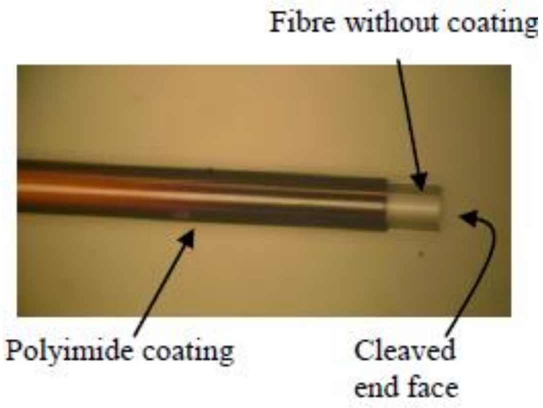
Closed mould : Not visible



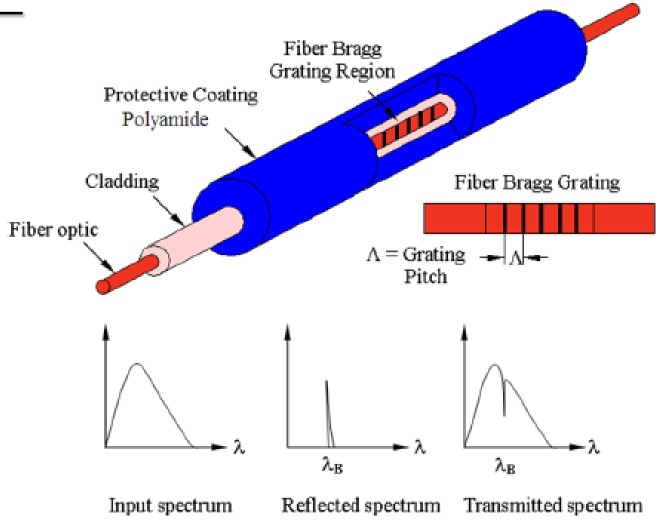
Sensor-based monitoring

- Conventional sensors suffer from limitations in:
  - ✓ Multi-point capability
  - ✓ Placement flexibility
  - ✓ Robustness in RTM environments
  - ✓ Potential disturbance to FRP geometry

End-Face Optical Fiber Sensor[9)]

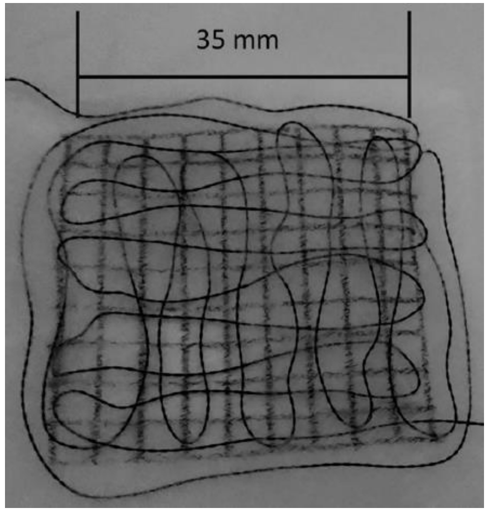


FBG Sensor [10)]



Pressure Sensor [11)]

Dielectric Sensor [12)]



9) W. Chehura, etc.,R. Jarzebinska, E. F. R. Da Costa, A. A. Skordos, S. W. James, I. K. Partridge, R. P. Tatam, Proc. of SPIE Vol. 8693 86930F-1, (2013)

10) M. Yildiz, N. G. Ozdemir, G. Bektas, Journal of Manufacturing Science and Engineering, vol. 134, (2012)

11)https://technology.nasa.gov/patent/LEW-TOPS-115

11) T. Mesogitis, G. Maistros, M. Asareh, C. Lira, A. Skordos, Composites: Part A 140 (2021) 106190

3. Resin Flow Sensor - Existing Sensor

- Conventional sensors suffer from limitations in:
  - ✓ Multi-point capability
  - ✓ Placement flexibility
  - ✓ Robustness in RTM environments
  - ✓ Potential disturbance to FRP geometry

Category	Sensor type	Multi-point capability	Placement flexibility	Robustness	Impact on FRP geometry
Optical	End-Face Optical Sensor	Not suitable	Limited	Robust	Potential disturbance
Optical	Fiber Bragg Grating (FBG)	Good	Limited	Sensitive to environment	Potential disturbance
Dielectric	Dielectric Sensor	Good	Limited	Sensitive to fiber contact	Potential disturbance
Pressure	Pressure Sensor	Not suitable	Limited	Robust	No impact

3. Resin Flow Sensor - PWG-Based Multi-Point Sensor

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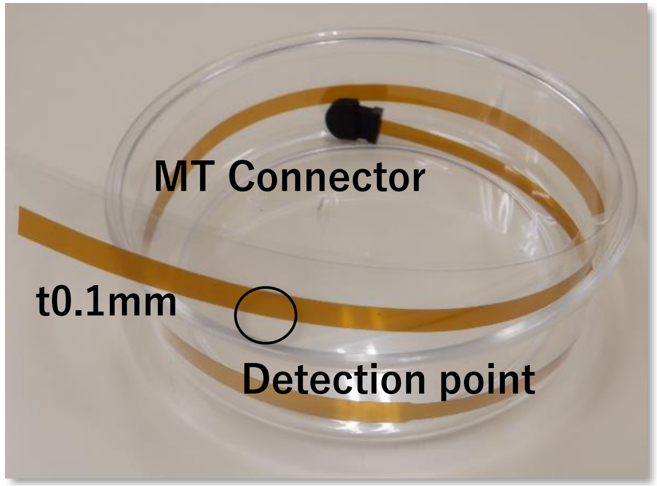
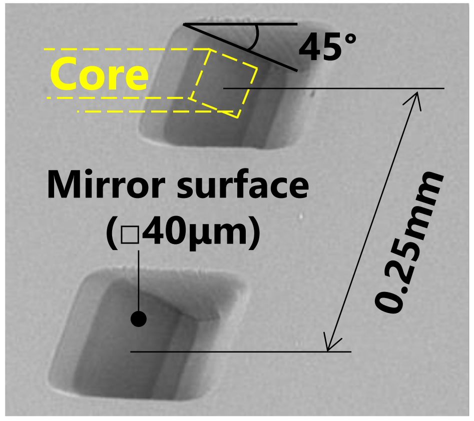
- ✓ Polymer optical waveguide (PWG) sensor fabricated on a polyimide (PI) film substrate
- ✓ Integration of **12 sensing points**
- ✓ Ultra-thin design: **0.1 mm** - Applicable to **curved surfaces**
  - **Minimal impact on FRP surface geometry**
- ✓ **Easy repositioning** without major mould modification
- ✓ Maximum length: ~ 3 m
- ✓ Operating temperature : ~ 120° C (expected up to 180° C)





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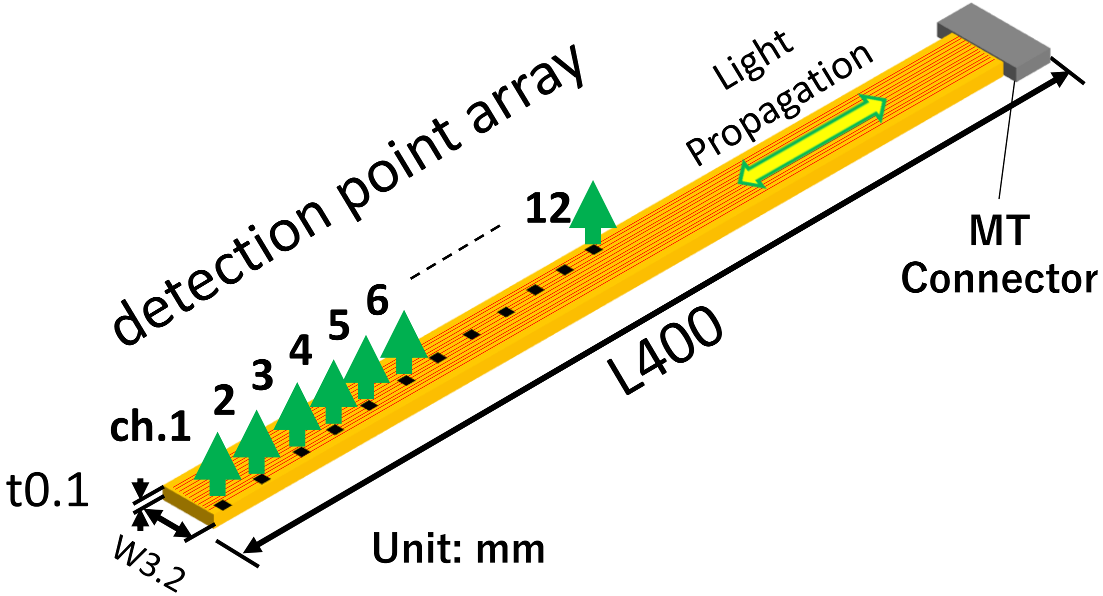
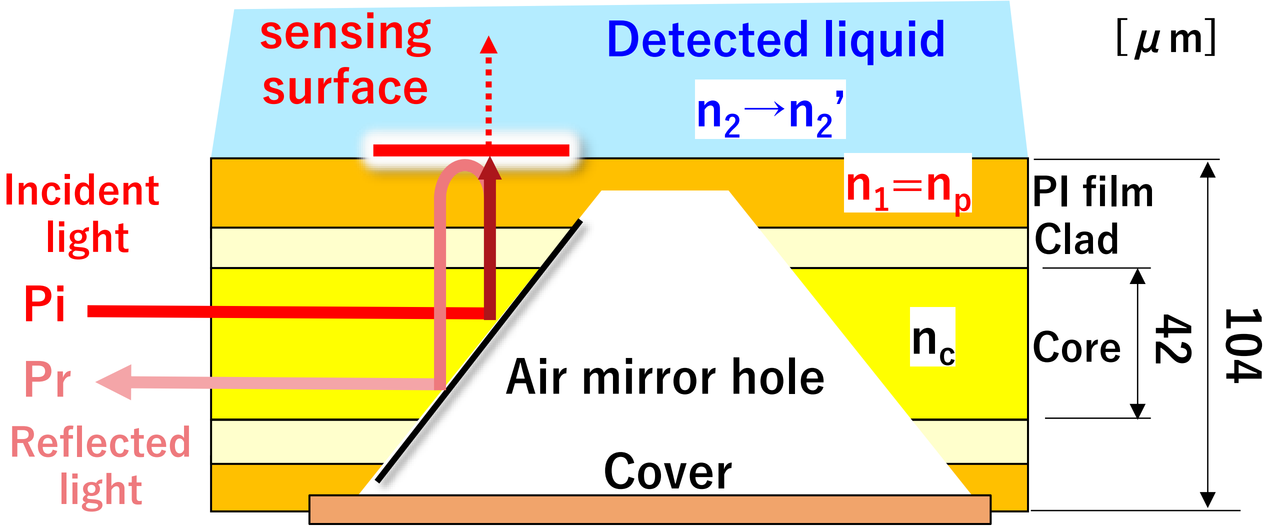


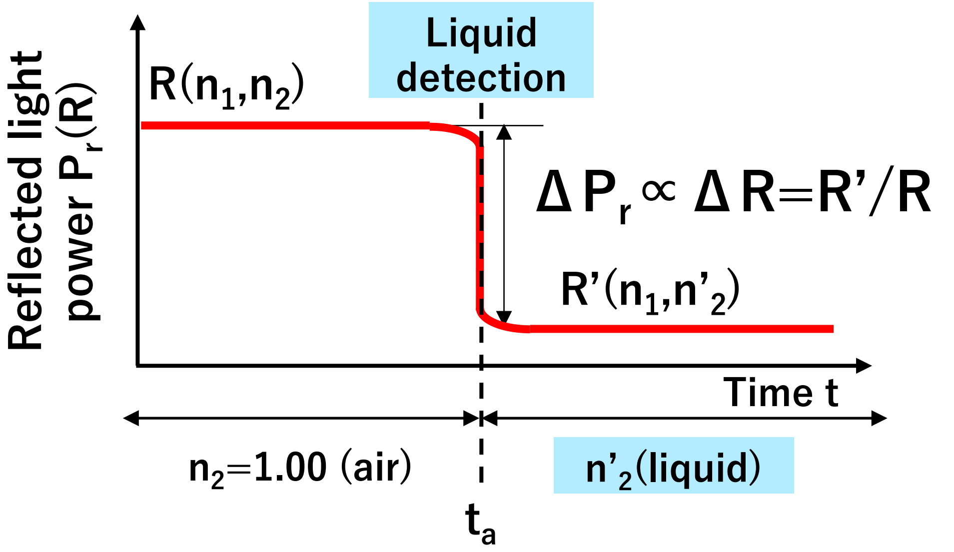
3. Resin Flow Sensor - PWG-Based Multi-Point Sensor

- Light propagates through the polymer optical waveguide
- At the detection site, light is reflected due to Fresnel reflection
- When resin reaches the surface, the refractive index changes
  → Reflectivity decreases, resulting in **a drop in reflected light intensity**

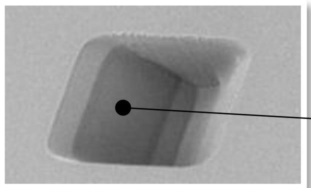
Cross-Sectional Image



Reflectivity decreases due to refractive index change



SEM Image of surface
(without cover)



Mirror surface (□40μm)

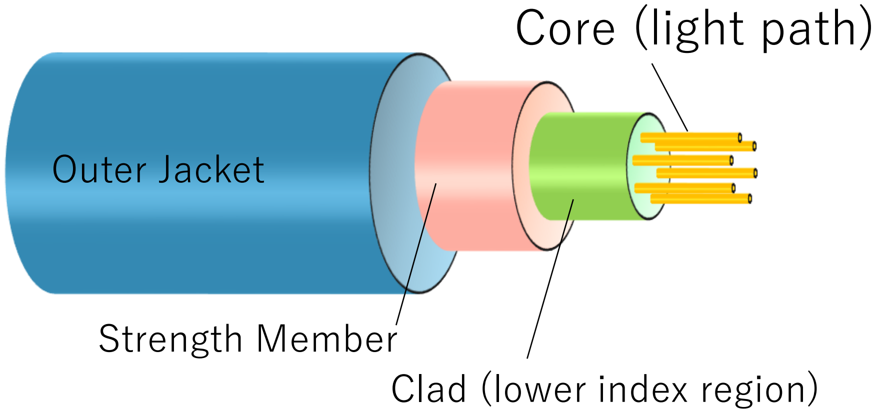
$R(n_1, n_2)$: Fresnel reflection coefficient
n_1: Refractive index of the sensor detection surface (PI surface, core surface)
n_2: Refractive index of the measured medium (e.g., air: n_2, resin: n'_2)
ΔR: Relative Fresnel reflectivity (normalized by the reflectivity in air)

3. Resin Flow Sensor -What is PWG?

- Polymer optical waveguides are widely used for high-density optical interconnections.
- They offer greater layout flexibility than conventional optical fibers.

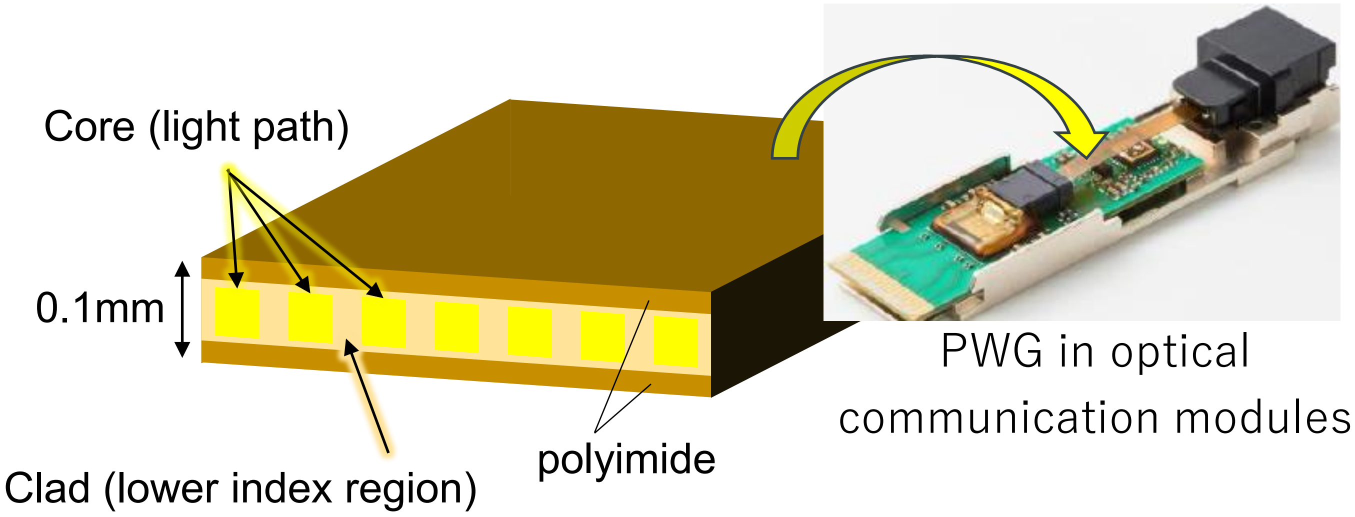
Conventional Optical Fibers

- ✓ Long-distance
- ✓ Low routing density



Polymer Optical Waveguide (PWG)

- ✓ Short-distance
- ✓ High-density
- ✓ Flexible routing



3. Resin Flow Sensor

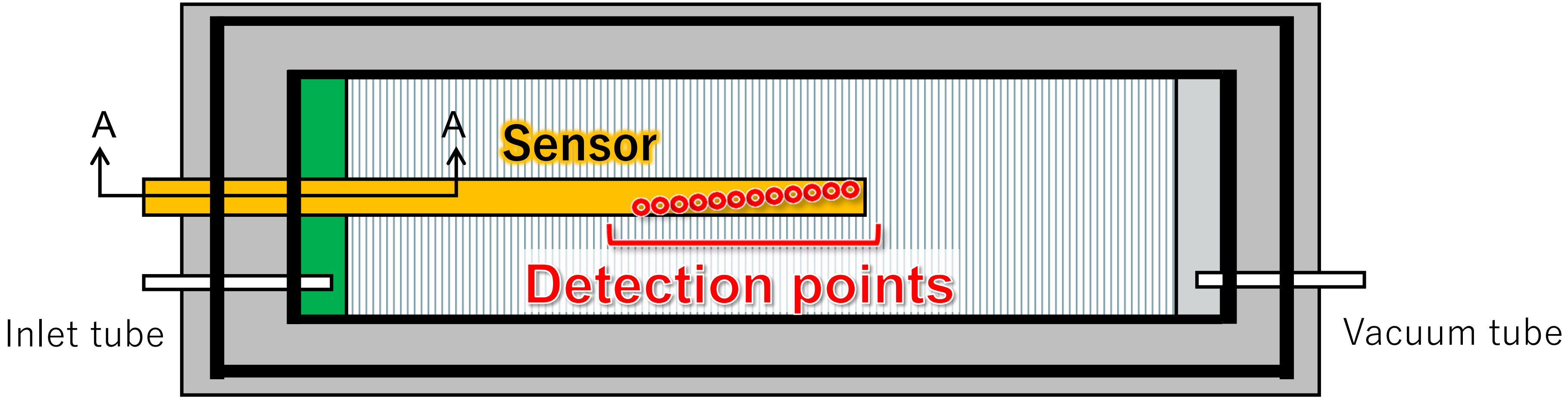
✓ The PWG sensor satisfies all key requirements for RTM flow monitoring

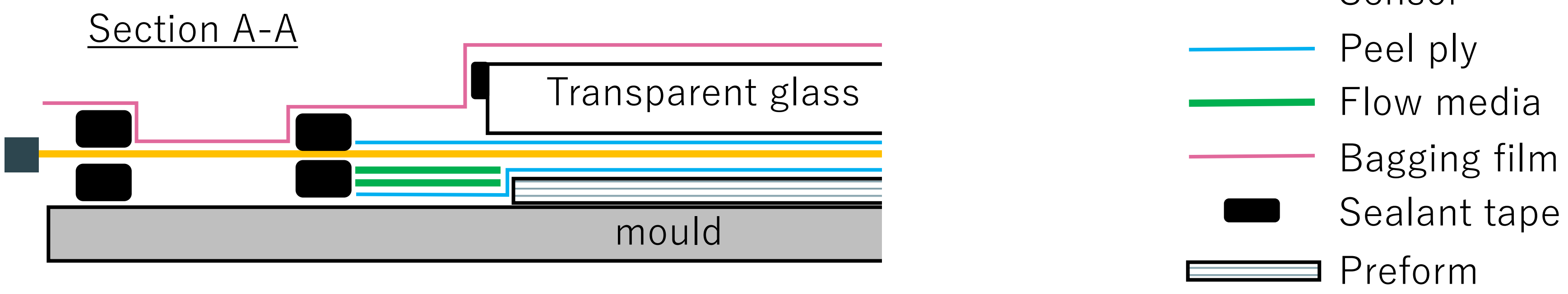
Comparison of Resin Flow Sensors

Category	Sensor type	Multi-point capability	Placement flexibility	Robustness	Impact on FRP geometry
Optical	**Polymer optical waveguide sensor**	Excellent	Excellent	Robust	Minimal impact
	End-Face Optical Sensor	Not suitable	Limited	Robust	Potential disturbance
	Fiber Bragg Grating (FBG)	Good	Limited	Sensitive to environment	Potential disturbance
Dielectric	Dielectric Sensor	Good	Limited	Sensitive to fiber contact	Potential disturbance
Pressure	Pressure Sensor	Not suitable	Limited	Robust	No impact

4. Validation test -Experimental Setup

- Flat preforms made of carbon fiber fabrics were used
- The PWG sensor was attached to the preform surface
- Resin was infused at 120° C

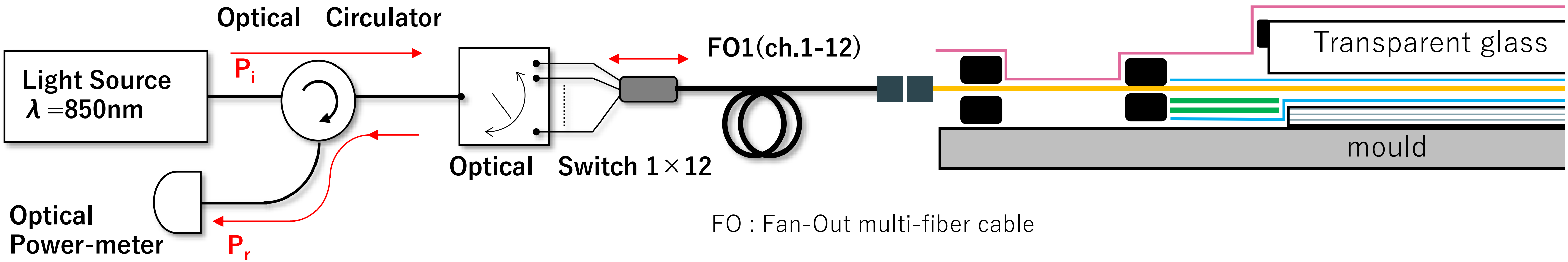




4. Validation test -Experimental Setup

- Light is supplied from a light source into the waveguides
- A mechanical optical switch sequentially selects each channel
- Reflected light from each sensing point is monitored using an optical power-meter
- Multi-channel measurements are performed in a cyclic manner

Measurement System



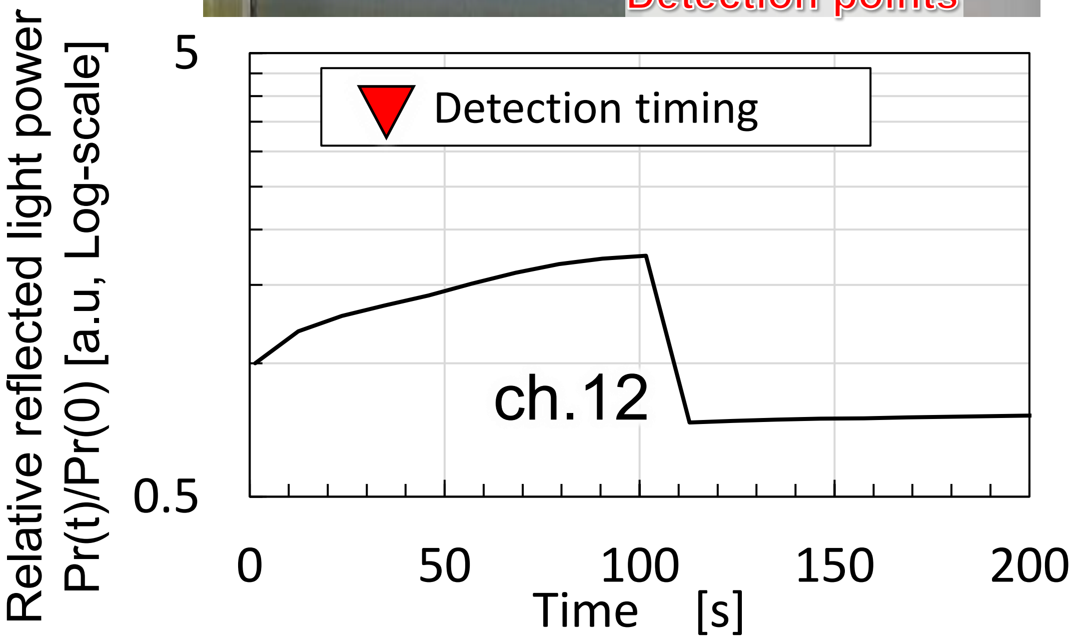
FO : Fan-Out multi-fiber cable

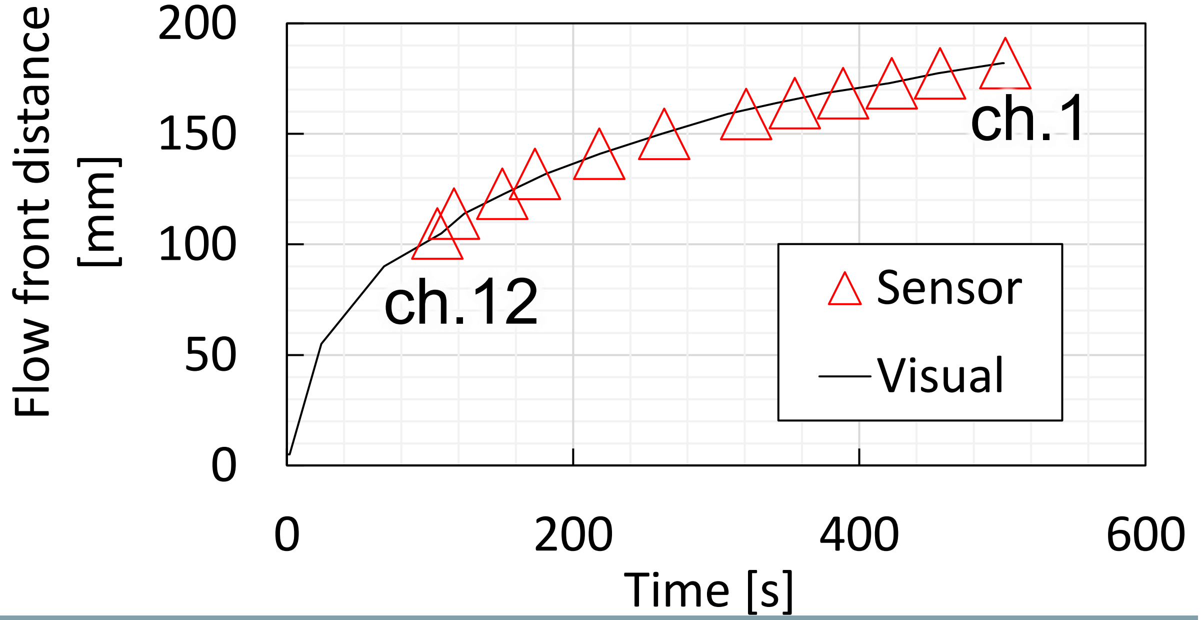
Measurement Cycle
Measurement time: 0.4 s per channel
Total time: 4.8 s (12 channels)

4. Validation test - Experimental Result

- Reflected intensity shows a clear drop at resin arrival
- Detection timing varies across channels, reflecting flow behavior
- Good agreement with visually observed flow front position

→ **Validation of the proposed sensing method**





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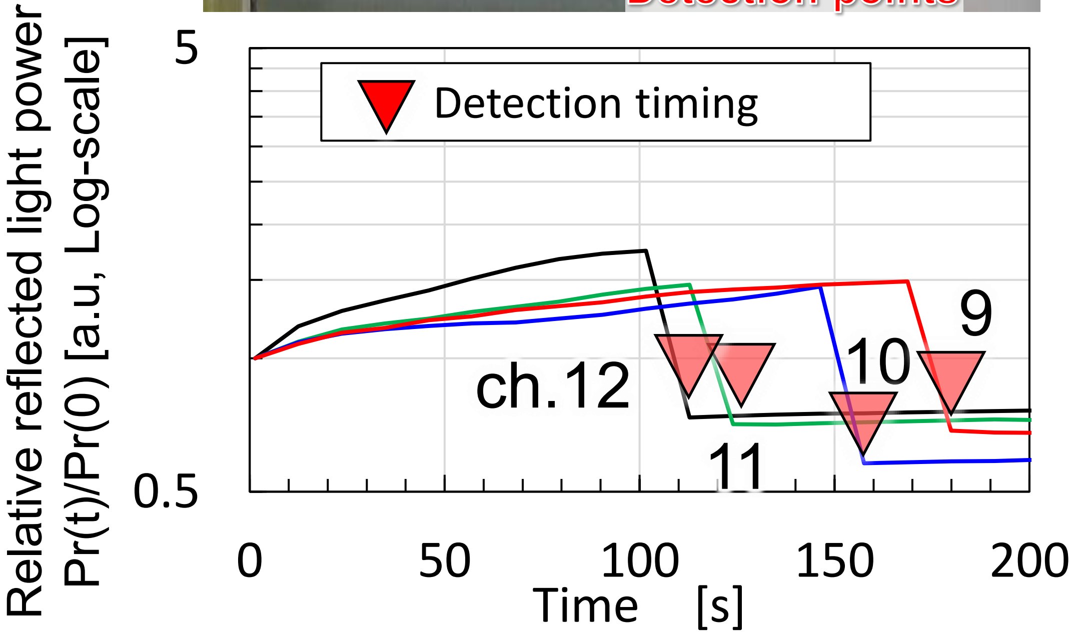
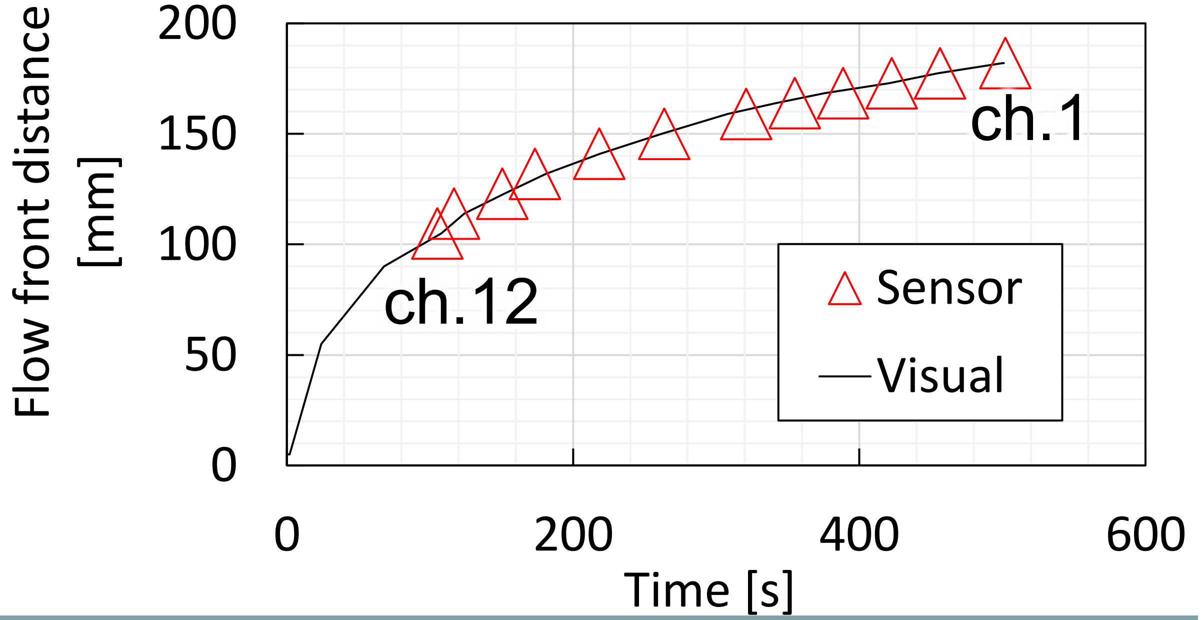
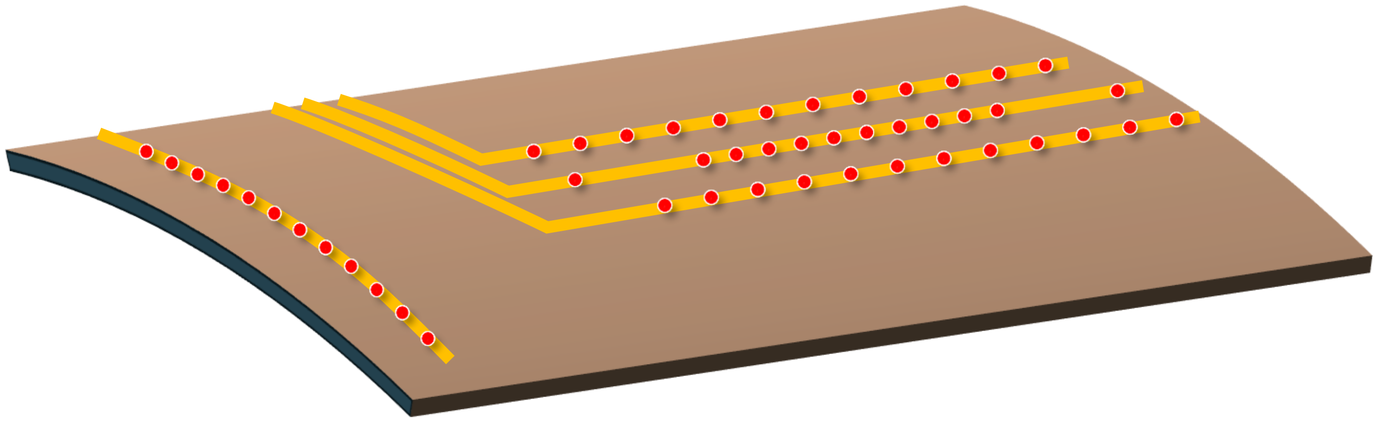


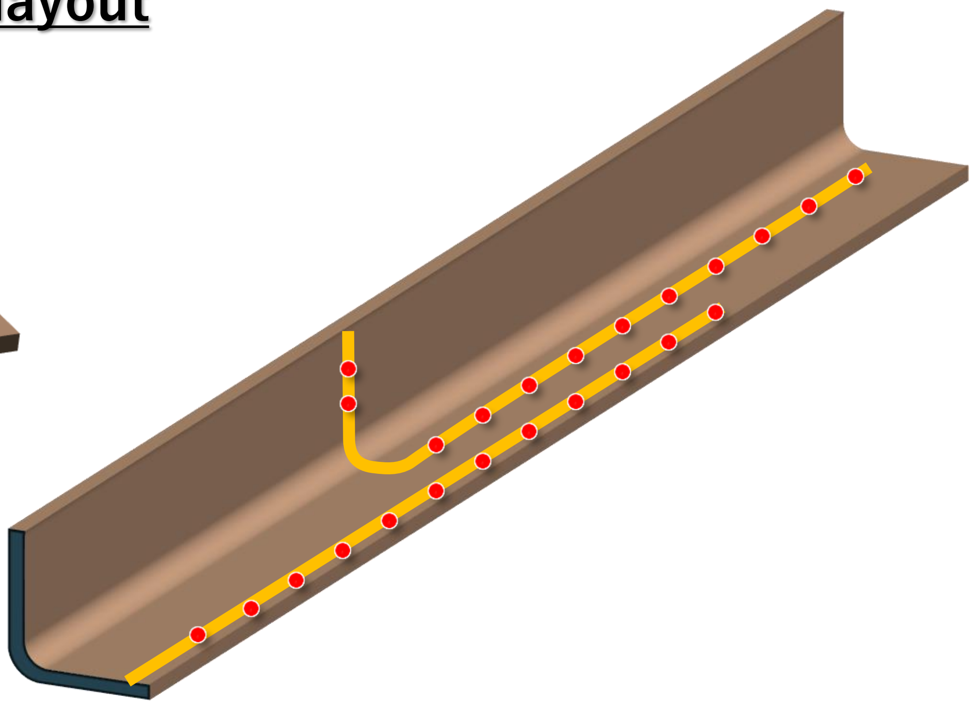


5. Application of PWG Sensor in RTM Prosses

- Multiple sensors can be installed simultaneously to cover wide areas
- Flexible sensing layout enables **adaptation to complex geometries**
- Supports both straight and **L-shaped configurations**
- Applicable even to regions with relatively **small radii of curvature**
- Disposable sensor suitable for integration into RTM processes

Customizable sensing layout





6. Conclusion

- A multi-point impregnation sensor based on PWG was developed
- The sensor enables real-time monitoring of resin flow in RTM
- Clear detection of resin arrival was achieved
- Good agreement with visual observation was confirmed
- Flexible, high-density sensor layout is applicable to complex structures

A promising approach for
in-situ monitoring in RTM processes

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Availability and Contact Information

Availability

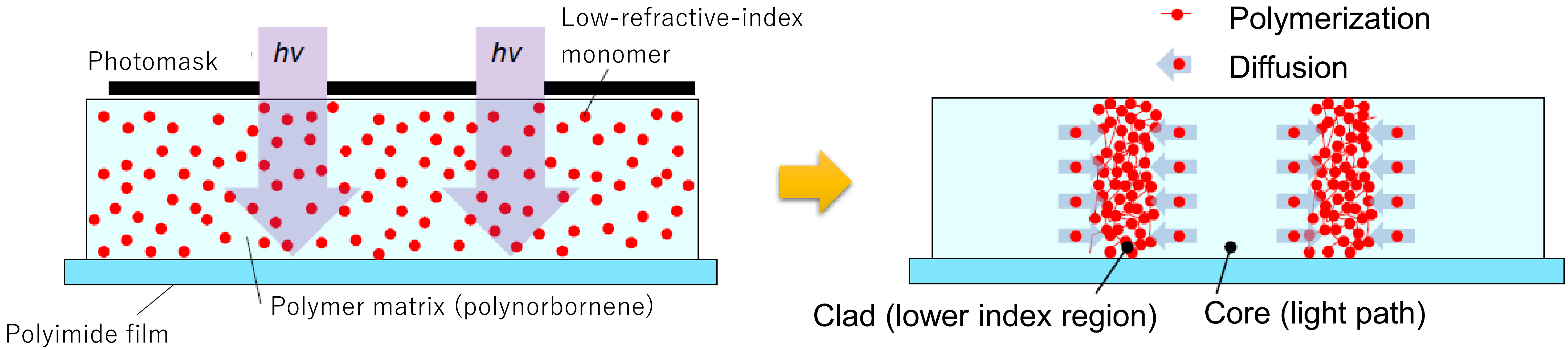
- The sensor is available from Sumitomo Bakelite Co., Ltd., although it is not yet in mass production

Contact Information

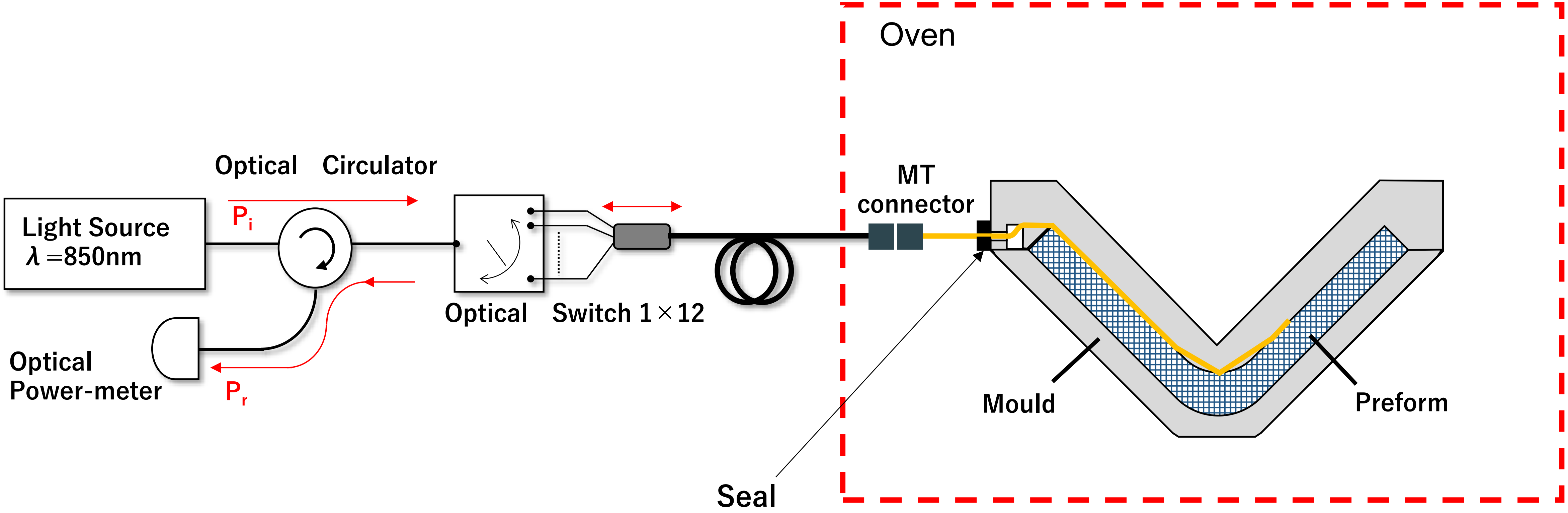
- Takeshi Fujita Mitsubishi Heavy Industries, Ltd. takeshi.fujita.an@mhi.com
- Toma TaniuchiSumitomo Bakelite Co., Ltd. taniuchi-toma@sumibe.co.jp

Manufacturing method of PWG

- A photomask is used to define the waveguide pattern
- Light irradiation (h ν) induces polymerization in the exposed regions
- As polymerization progresses, low-refractive-index monomers diffuse toward the irradiated area
- This diffusion process forms a refractive index distribution between core and cladding
- As a result, a polymer optical waveguide is formed within the polymer matrix (polynorbornene)



Measurement System



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