Theory of fiberoptic current sensors

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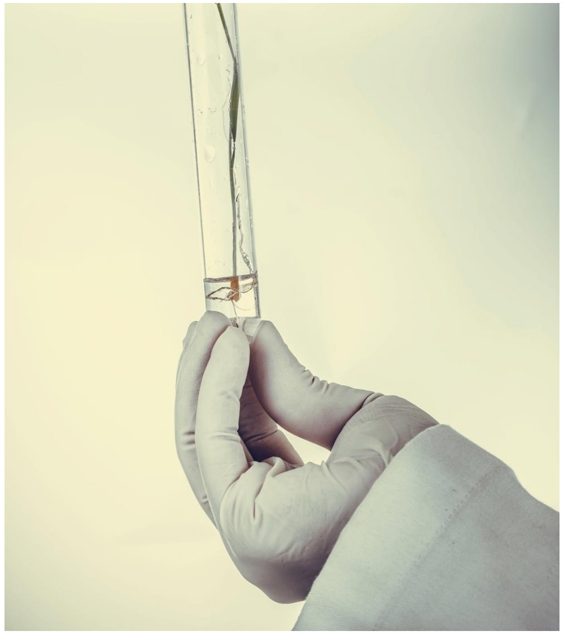
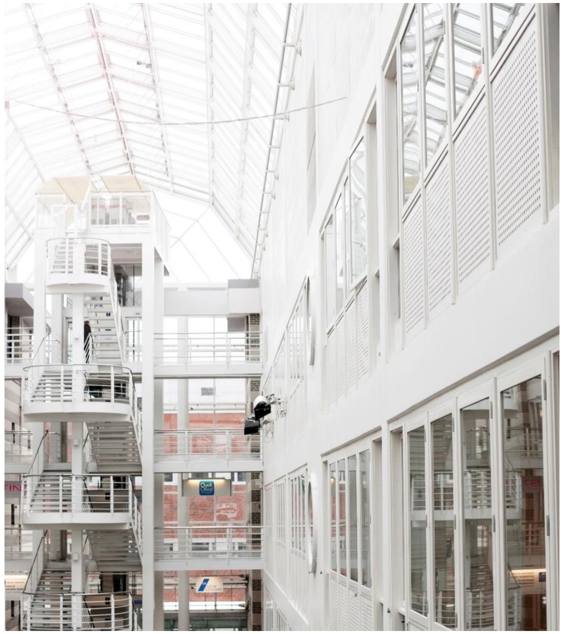
19 April 2017

Research Institutes of Sweden

Safety and Transport
Measurement Science and Technology – Time and optics



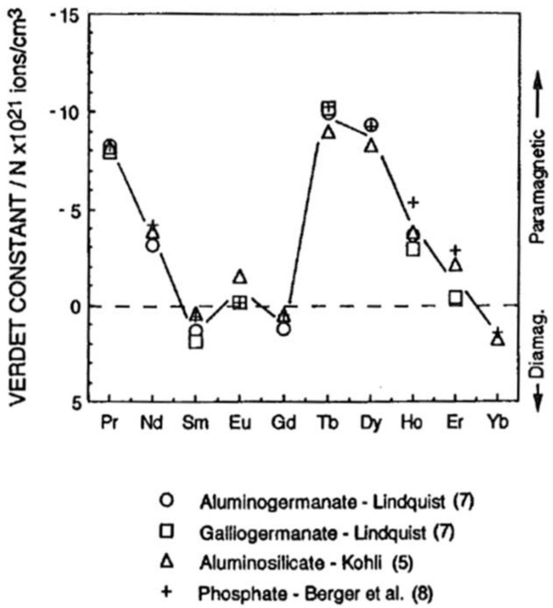


Theory of fiberoptic current sensors

- Background – the Faraday effect
- Polarization measurement
- Interferometric methods
- Phase modulation
- FOCS setup
- Fiber properties

Background – the Faraday effect

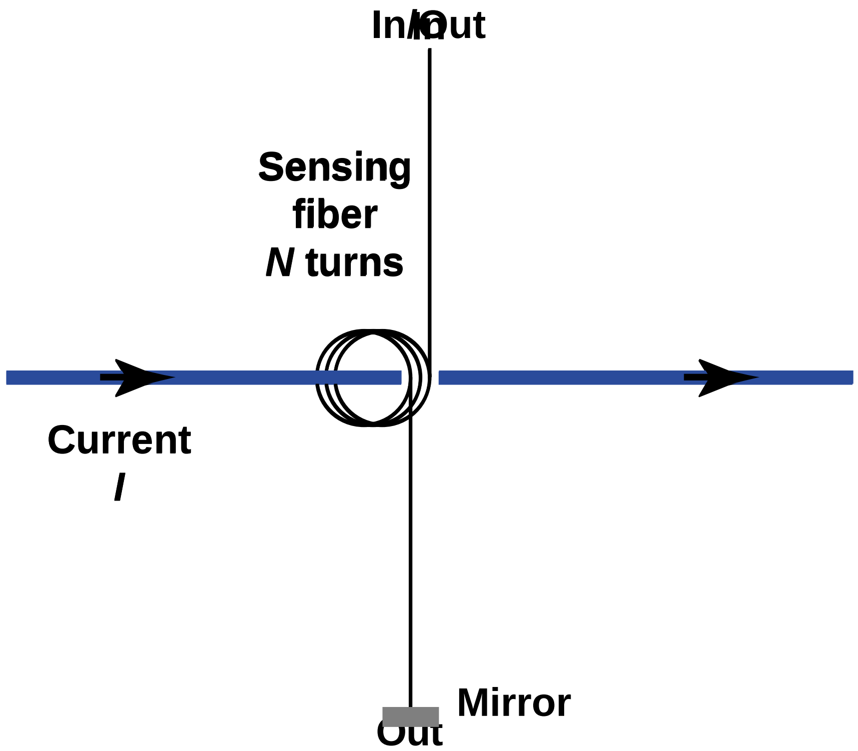
- Fibers are generally insensitive to disturbance
- Michael Faraday 1845: light is influenced by an external magnetic field
- Electro-optic modulator
- Nonreciprocal effect
- Verdet constant is material specific
- Doping with rare-earths may increase V



Material	Verdet constant V (10^{-3} min of arc G^{-1} cm^{-1})	Wavelength (nm)
H_2O	13,11	500
	12,6	600
	7,0	800
	4,4	1000
	2,9	1250
CCl_4	16,03	600
	8,9	800
	5,7	1000
	2,5	1500
	1,3	2000
C_6H_6	29,7	600
	15,3	800
	9,5	1000
	3,9	1500
	2,2	2000
CS_2	43,41	600
	21,4	800
	13,5	1000
	5,8	1500
	3,1	2000
ZnS	225	
NaCl	35,85	
KCl	28,58	
PbO SiO_2 (glass)	77,9	
Tb-doped glass	213	1053

Background – the Faraday effect

- Fiber coil instead
- N number of turns in coil
- Ampere's law gives a closed line integral: $\theta_\mathrm{f} = \mathrm{V} \oint \boldsymbol{B}\, d\boldsymbol{l} = \mu_0 \mathrm{V}\, N\, I$
- End mirror creates double passage

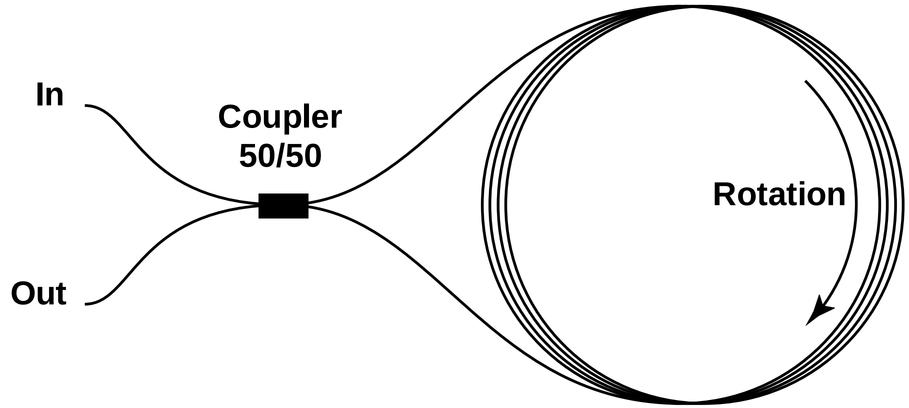


Polarization measurement

- Direct measurement of polarization
- Accuracy and speed
- Difficult to measure 50-Hz and harmonics

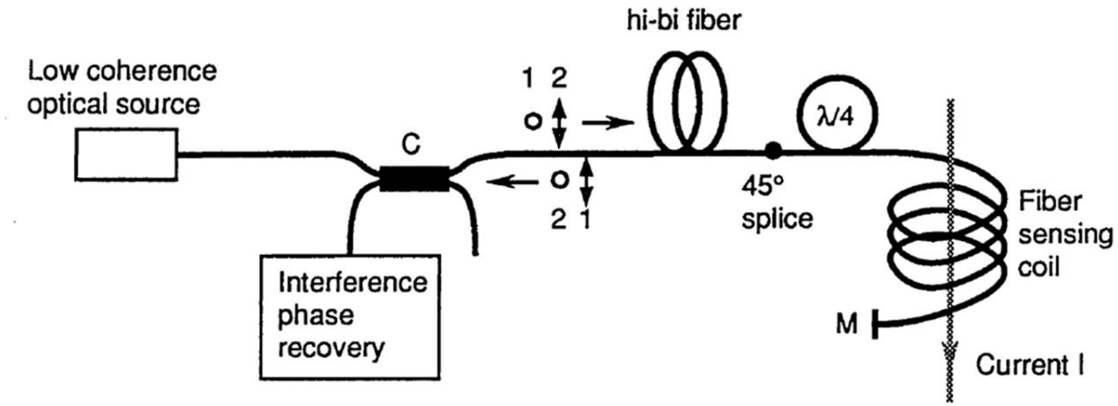
Interferometric methods

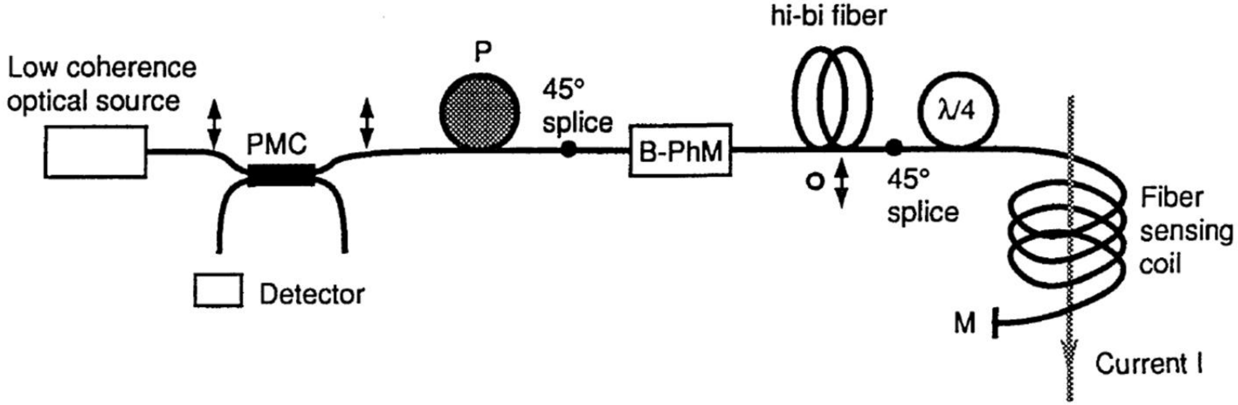
- Using a laser, the setup becomes an interferometer of the Sagnac type
- Fiberoptic gyroscope
- Extremely sensitive...
- ...to all changes in the fiber: length, temperature, vibration, etc.



Phase modulation

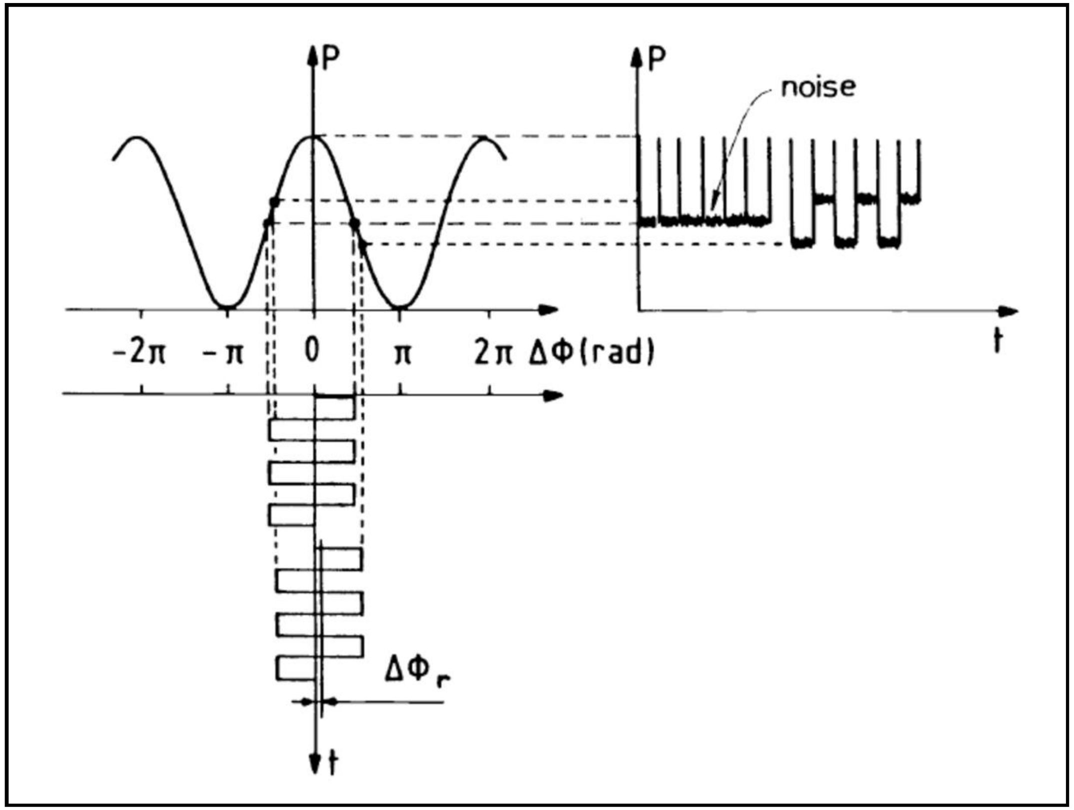
- Use a broadband source to avoid interferometric effects – superluminescent diode
- Frosio and Dändliker (1994)
- Highly nonlinear response
- Introduction of a phase modulator
- The detected intensity is proportional to an expression which can be expressed as the sum of Bessel functions





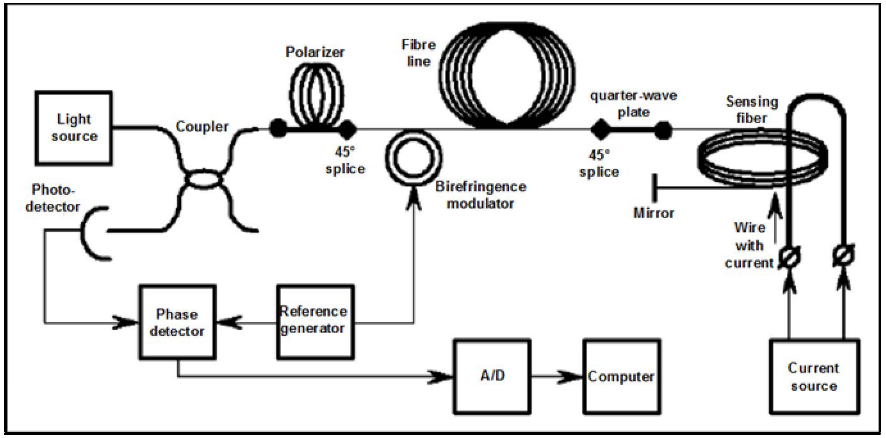
Square-wave modulation

- Sinewave response is nonlinear and can suffer from wrap-around
- H. C. Lefevre *et al.* (1990)
- Bias to linear regime
- PID regulation to keep the operating point



Profotech setup

- Use Jones-matrices to describe each component
- Polarization state is determined by the relative amplitude and relative phase
- Reciprocity means many errors cancel out
- Resulting power on the detector



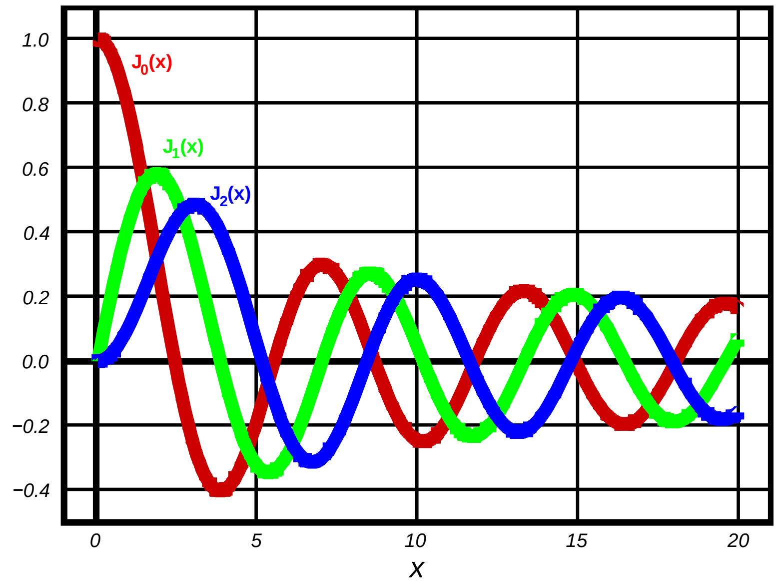
$$
\begin{aligned}
P(t) = \frac{P_0}{2} + \frac{P_0}{2} & J_0(4A_m \sin(\omega_0 \Delta t))[\mathrm{Re}^2(u) - \mathrm{Re}^2(v)] \\
& + \frac{P_0}{2} J_0(4A_m \cos(\omega_0 \Delta t))[\mathrm{Im}^2(u) - \mathrm{Im}^2(v)] \\
& + P_0 J_1(4A_m \sin(\omega_0 \Delta t)) \sin(\omega_0 t) 2\,\mathrm{Re}(u)\,\mathrm{Re}(v) \\
& - P_0 J_1(4A_m \cos(\omega_0 \Delta t)) \cos(\omega_0 t) 2\,\mathrm{Im}(u)\,\mathrm{Im}(v) \\
& + P_0 J_2(4A_m \sin(\omega_0 \Delta t)) \cos(2\omega_0 t)[\mathrm{Re}^2(u) - \mathrm{Re}^2(v)] \\
& - P_0 J_2(4A_m \cos(\omega_0 \Delta t)) \cos(2\omega_0 t)[\mathrm{Im}^2(u) - \mathrm{Im}^2(v)]
\end{aligned}
$$

FOCS setup

- Bessel functions result from Fourier-expansion
- Two parameters can be chosen to linearize the response – A_m and w_0

$$J_1(4A_m \sin(\omega_0 \Delta t)) = J_2(4A_m \sin(\omega_0 \Delta t))$$

$$J_2(4A_m \cos(\omega_0 \Delta t)) = 0$$



$$\begin{aligned}
P(t) = \frac{P_0}{2} &+ \frac{P_0}{2} J_0(4A_m \sin(\omega_0 \Delta t))[\mathrm{Re}^2(u) - \mathrm{Re}^2(v)] \\
&+ \frac{P_0}{2} J_0(4A_m \cos(\omega_0 \Delta t))[\mathrm{Im}^2(u) - \mathrm{Im}^2(v)] \\
&+ P_0 J_1(4A_m \sin(\omega_0 \Delta t)) \sin(\omega_0 t) 2\,\mathrm{Re}(u)\,\mathrm{Re}(v) \\
&- P_0 J_1(4A_m \cos(\omega_0 \Delta t)) \cos(\omega_0 t) 2\,\mathrm{Im}(u)\,\mathrm{Im}(v) \\
&+ P_0 J_2(4A_m \sin(\omega_0 \Delta t)) \cos(2\omega_0 t)[\mathrm{Re}^2(u) - \mathrm{Re}^2(v)] \\
&- P_0 J_2(4A_m \cos(\omega_0 \Delta t)) \cos(2\omega_0 t)[\mathrm{Im}^2(u) - \mathrm{Im}^2(v)]
\end{aligned}$$

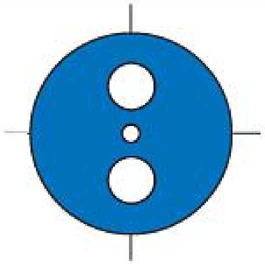
FOCS setup

- Detect the signal at w_0 and $2w_0$ using a lock-in amplifier
- The ratio is proportional to the polarization change q_f, which is proportional to the current $I(t)$
- $\tan\theta_f \propto \frac{P_{\cos(2\omega_0 t)}(t)}{P_{\cos(\omega_0 t)}(t)}$, where $\theta_\mathrm{f} = \mathrm{V} \oint \boldsymbol{B}\, d\boldsymbol{l} = \mu_0 \mathrm{V}\, N\, I(t)$

Fiber properties

- Short wavelength – increases the Verdet constant
- Possibly doping – increases the Verdet constant
- Fiber has bending-induced birefringence which may mask the effect – use spun fiber
- Polarization maintaining (PM) fiber – since we are measuring polarization

Bow-tie type



Panda type

THANK YOU!

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