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MULTISTAGE SPECTRAL POLARIMETER FOR WDM SYSTEM SURVEILLANCE

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Abstract

A 4-stage spectral polarimeter based on Ti:LiNbO$_3$ acoustooptical TE-TM converters has been realized. It has about 20 dB stopband suppression and can measure polarimetric spectra as well as the time evolution of the state of polarization.

1. Introduction

Optical WDM systems require precise channel frequency setting. Fiber four-wave mixing can limit the performance of such systems. However, it is a polarization-dependent process and may be reduced if adjacent channels carry different polarizations. For the operation of high-performance WDM systems, especially on trunk lines, a polarization-sensitive spectrometer is therefore advisable. It is readily built by placing a polarimeter [1–3] behind a narrowband optical filter.

We present a simpler approach in which the filter **is** the polarimeter: A Ti:LiNbO$_3$ acoustooptical TE-TM [4, 5] converter followed by a polarizer can be used to realize a wavelength-selective polarimeter [6]. Its stopband attenuation is increased by adding more mode converters on the same chip. A value of > 28 dB has been measured in a 4-stage device [7]. However, only the filtering function was demonstrated with this high stopband attenuation. Here we will present a fully engineered spectral polarimeter, and demonstrate its capability to measure the state-of-polarization of individual lasers. The impact of unpolarized EDFA noise is also discussed.

2. Theory

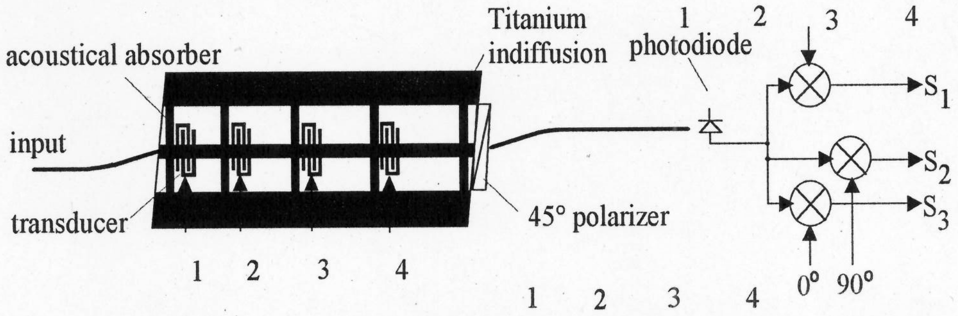

Fig. 1: 4-stage spectral polarimeter with LiNbO$_3$ acoustooptical TE-TM converter. Section lengths are 3.8, 6.3, 7.6 and 7.5 mm which allows to notch out the sidelobes of one mode converter by the zeros of another.

A piezoelectrical interdigital transducer that is driven by an RF signal generates a moving acoustical density grating in an x-cut, y-propagation Ti:LiNbO$_3$ crystal. The Jones matrix of this TE-TM mode converter is

$$\mathbf{J} = \begin{bmatrix} A & B \\ -B^* & A^* \end{bmatrix} \quad A = e^{-jkl/2}\left(\cos(\mu l) - j\frac{\delta}{\mu}\sin(\mu l)\right) \quad B = je^{j(\omega t - kl/2)}\frac{\kappa}{\mu}\sin(\mu l)$$

for uniform acoustooptical interaction, electrical and acoustical angular frequency ω, coupling constant κ, detuning $\delta = (\beta_{TM} - \beta_{TE} - k)/2$, acoustical propagation constant $k = |\omega|/v_{ac}$, (positive) acoustical velocity v_{ac}, interaction length l, and $\mu = \sqrt{\kappa^2 + \delta^2}$. For co-propagation of light and sound waves $\omega > 0$ is valid, else $\omega < 0$. Furthermore lossless operation has been assumed because $|A|^2 + |B|^2 = 1$. Consider now the setup of Fig. 1 but ignore all but the first mode converter.

The light whose state-of-polarization is to be measured (Jones vector: $\mathbf{E}$) is passed through mode converter 1. In a photodiode behind a 45° linear polarizer (Jones vector of transmitted eigenmode: $\mathbf{E}_{pol} = [1 \quad 1]^T/\sqrt{2}$) beat notes between TE and TM waves at the mode converter output are observed. Depending on input polarization the frequency difference between these TE and TM components is either ω_1 or $2\omega_1$. When expressed as a function of input Stokes parameters the intensity $I = \left|\mathbf{E}_{pol}^{+}\mathbf{M}_1\mathbf{E}\right|^2$ is

$$I = \left(p\cos(\omega_1 t - k_1 l_1) + q\sin(\omega_1 t - k_1 l_1)\right)S_1 + \frac{g_1}{2}\left(\cos(2\omega_1 t - k_1 l_1)S_2 + \sin(2\omega_1 t - k_1 l_1)S_3\right) + \mathrm{DC}$$

where $p = -\left(\delta_1\kappa_1/\mu_1^2\right)\sin^2(\mu_1 l_1) \quad q = (\kappa_1/(2\mu_1))\sin(2\mu_1 l_1)$

$$f = \sqrt{p^2 + q^2} = (1/2)\sin\left(2\arcsin\left((\kappa_1/\mu_1)\sin(\mu_1 l_1)\right)\right) \qquad g_1 = \left((\kappa_1/\mu_1)\sin(\mu_1 l_1)\right)^2 .$$

Stokes parameters S_1 and S_2, S_3 are obtained by phase-sensitive detection at ω_1 and $2\omega_1$, and are spectrally filtered by q and g_1, respectively (Fig. 2). Normally half conversion $2\kappa_1 l_1 = \pi/2$ is chosen. No filtering applies for S_0 which is part of the DC term. The wavelength can therefore be measured only for polarized signals.

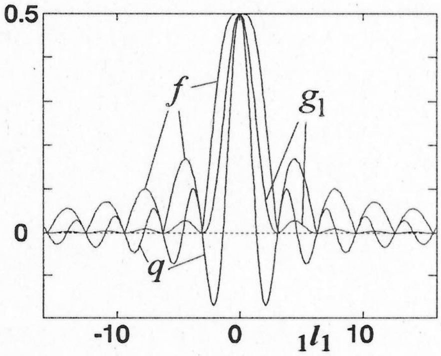

Fig. 2: Functions f, q, and g_1 in single-stage polarimeter (theory)

Now consider more mode converters, with acoustical frequencies ω_i, $i = 2 \ldots n$, placed between first converter and polarizer. For full conversion $2\kappa_i l_i = \pi$ TE and TM components are interchanged in each of them and frequency-shifted up and down, respectively, by ω_i. The interesting intensity components in the multistage spectral polarimeter are

$$g_2 g_3 \cdot \ldots \cdot \left(\left(p\cos(\Omega_1 t - \Psi) + q\sin(\Omega_1 t - \Psi)\right)S_1 + \frac{g_1}{2}\left(\cos(\Omega_{2,3}t - \Psi)S_2 + \sin(\Omega_{2,3}t - \Psi)S_3\right)\right)$$

where $\Omega_1 = \Omega_{2,3} - \omega_1 \quad \Omega_{2,3} = 2(\omega_1 - \omega_2 + \omega_3 - \ldots + \ldots) \quad \Psi = k_1 l_1 - k_2 l_2 + k_3 l_3 - \ldots + \ldots$.

Leading multiplicands g_i express optical filtering in mode converters $2 \ldots n$. They apply because Ω_1, $\Omega_{2,3}$ are chosen as detection frequencies. Limited only by thermal, shot and intensity noises this concept allows in principle to achieve an arbitrarily high stopband attenuation in the spectral polarimeter, provided ω_i are chosen such that Ω_1, $\Omega_{2,3}$ are generated uniquely by frequency shifts - hence filtering - in all n stages. This imposes $\omega_i + (-1)^m \omega_{i+m} \neq 0$ and other similar conditions.

3. Experiment

A 4-stage spectral polarimeter according to Fig. 1 was realized. The chip carries 4 mode converters and is packaged with slanted endfaces, SMF at the input, and a laminated polarizer followed by a graded-index photodiode pigtail at the output. The even number of stages and the co-propagation of light and sound in all mode converters yield detection frequencies Ω_1, $\Omega_{2,3}$ near ω_1 and near zero, respectively. This keeps the required signal processing bandwidth low. Fig. 3 shows schematic and frequency response of the front end. The peak at Ω_1 is not fully visible. Offsets of $\omega_{2...4}$ with respect to ω_1 were -22.4, -182.4 and -28.8 kHz, respectively, and the lower peak was therefore tuned to 262 kHz while the higher one is around 175 MHz. Synthesizers supply tunable frequencies for the acoustooptical mode converters, and a mixer chain generates the detection frequencies with the required suppression of spurious signals.

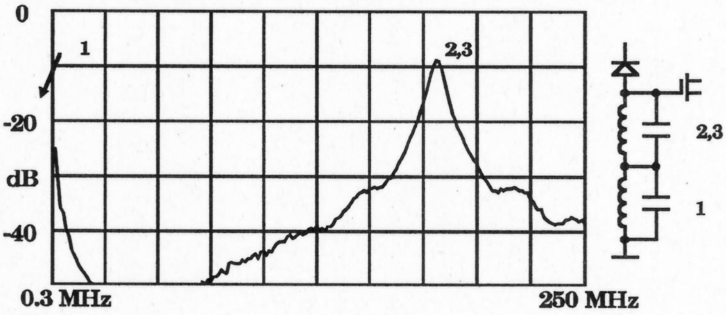

Fig. 3: Double-resonant high-impedance front end

The instrument has spectral and temporal display routines. In the latter mode polarimetric traces of normalized Stokes parameters were recorded at a fixed wavelength of 1546 nm (Fig. 4). The optical input power was about -36 dBm. For this input power measurement accuracy is about 0.005 for S_1, and 0.01 for S_2, S_3.

Another laser with a wavelength of 1552 nm was added and the instrument was operated in its spectral display mode with an electrical frequency sweep (Fig. 5).

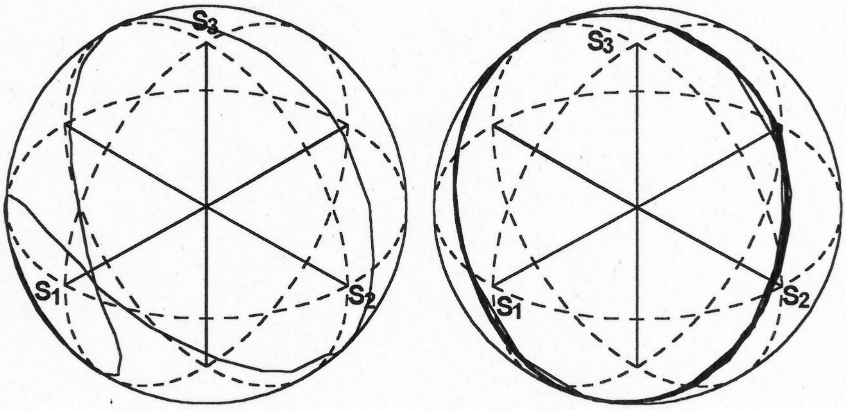

Fig. 4: Polarimetric traces of rotated fiber coil (quarterwave plate; left) and polarization-maintaining fiber (100 m having a differential group delay of ~200 ps) with temperature drift and both principal states about equally exited (right)

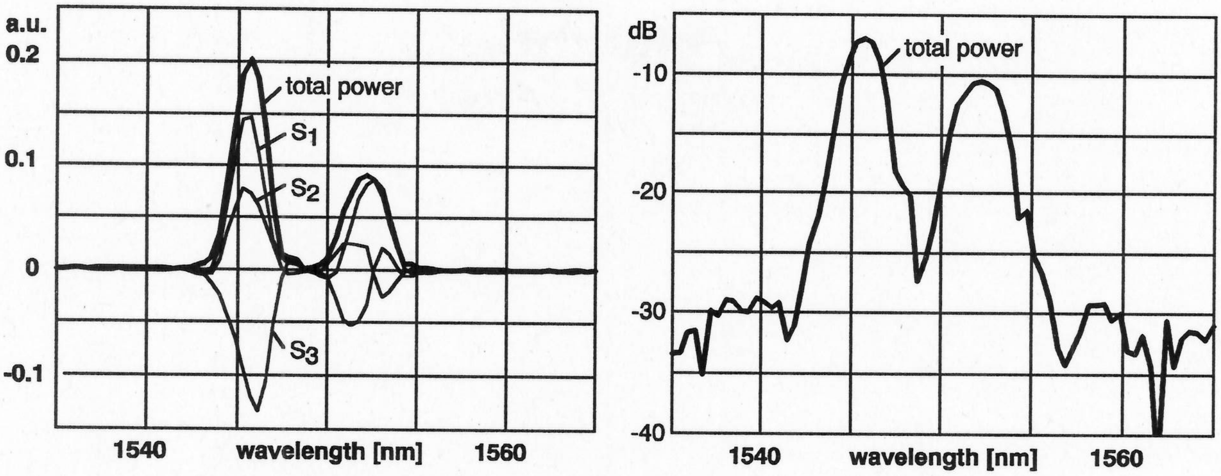

Fig. 5: Polarimetric spectrum (left) and logarithmic power spectrum (right) of two laser signals

The two lasers exhibited different states-of-polarization. A logarithmic magnitude plot reveals a sidelobe suppression of some 20 dB optical for our instrument.

Remember that unpolarized signals will be suppressed. Fig. 6 shows therefore the noise spectrum of an EDFA with a subsequent fiber polarizer. The low-periodicity frequency dependence is determined by Ψ as well as by cable lengths inside the instrument which cause phase delays that are different for the two detection frequencies. It may be calibrated away so that a frequency-independent polarimetric display should be possible.

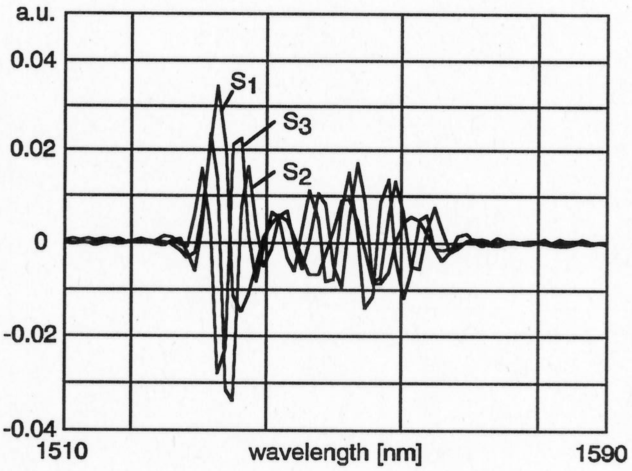

Fig. 6: Polarimetric spectrum of EDFA noise filtered by a fiber polarizer. Low-periodicity frequency dependence could be calibrated away.

4. Conclusions

A 4-stage spectral polarimeter based on Ti:LiNbO$_3$ acoustooptical TE-TM converters has been realized. It has about 20 dB stopband suppression and can measure polarimetric spectra as well as the time evolution of the state of polarization.

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