Mueller Matrix based Modeling of Nonlinear Polarization Rotation in a Tensile-Strained Bulk SOA

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Outline

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Introduction

Nonlinear polarization rotation (NPR) in SOAs has attracted much interest for use in all-optical signal processing applications such as wavelength conversion and optical logic*.

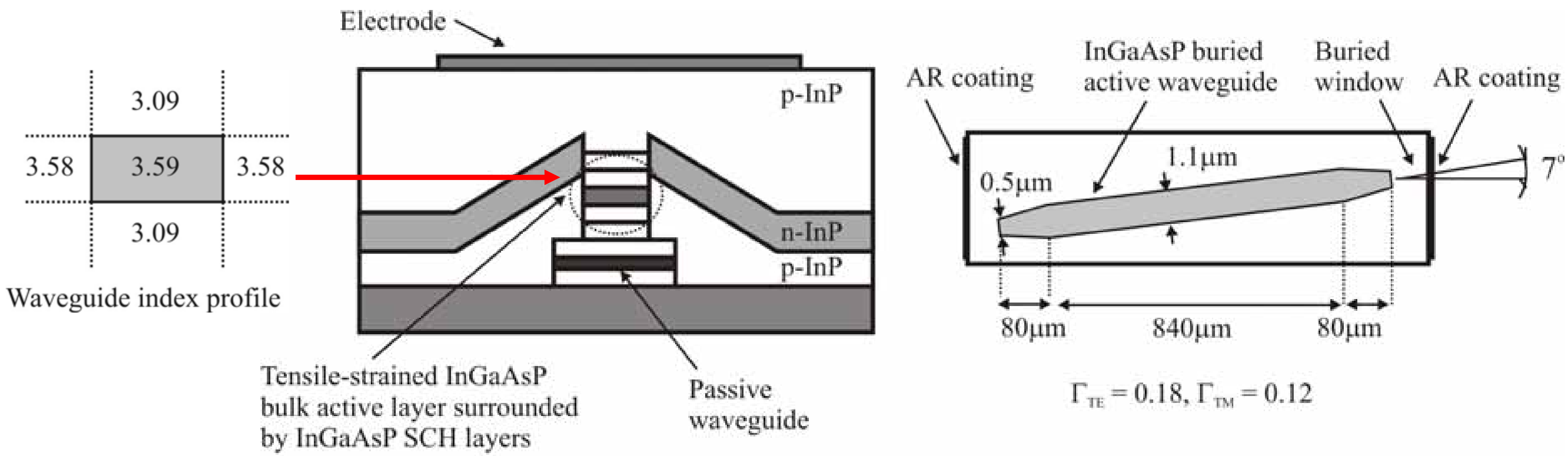
There is a need for detailed models that can predict NPR, which pay close attention to the underlying physics of a particular SOA structure and material.

We model NPR induced on a probe signal due to a co-propagating pump signal in a tensile-strained bulk SOA, using a Mueller matrix approach.

* L.Q. Guo and M.J. Connelly, *J. Lightwave Technol.*, 2005.

Tensile-Strained SOA

Tensile-strained bulk SOAs have attracted much interest due to its relative ease of fabrication and commercial devices are now available.



(a) Cross-section of the SCH SOA structure.

(b) Top view of the active waveguide.

Device geometry and some material parameters supplied by *Amphotonics** *(Kamelian)*.

* C. Michie et al., *J. Lightwave Technol.*, 2006.

Steady-state model

We have previously developed a wideband steady-state model* that can be used to predict the tensile-strained SOA behaviour without the use of any adjustable parameters.

– uses a detailed model for the material band-structure.

For a given bias current and input signal powers the model can be used to predict the spatial distribution of the carrier density.

* M.J. Connelly, *IEEE J. Quantum Electron.*, 2007

Non-Linear Polarization Rotation

NPR in an SOA is caused by the *carrier density dependence* of the TE and TM mode active region refractive index. The polarization state of a weak probe signal can be changed by the presence of a strong pump.

The NPR of the probe can be modeled using Mueller matrices*. If the Stokes vector S_i of the input probe signal is known, then the probe output Stokes vector is

$$S = MS_i$$

where M is the SOA Mueller matrix.
This is particularly useful because it is easy to measure Stokes vectors using a polarisation analyser.

* L.Q. Guo and M.J. Connelly, *J. Lightwave Technol.*, 2007.

Stokes Parameters

Any state of polarized light can be described by 4 measurable quantities (Stokes parameters or vector) $(S_0, S_1, S_2, S_3)^T$.

A plane wave propagating in the *z* direction can be considered to be the sum of two orthogonal plane waves.

$$E_x(t) = E_{0x}(t)\cos[\omega t + \delta_x(t)] \text{ and } E_y(t) = E_{0y}(t)\cos[\omega t + \delta_y(t)]$$

It can be shown that

$$\left(E_{0x}^2 + E_{0y}^2\right)^2 - \left(E_{0x}^2 - E_{0y}^2\right)^2 - \left(2E_{0x}E_{0y}\cos\delta\right)^2 = \left(2E_{0x}E_{0y}\sin\delta\right)^2$$

or $S_0^2 = S_1^2 + S_2^2 + S_3^2$

$$\delta = \delta_y - \delta_x$$

S_0 is the total light intensity.

S_1 describes the amount of linear horizontal or vertical polarization.

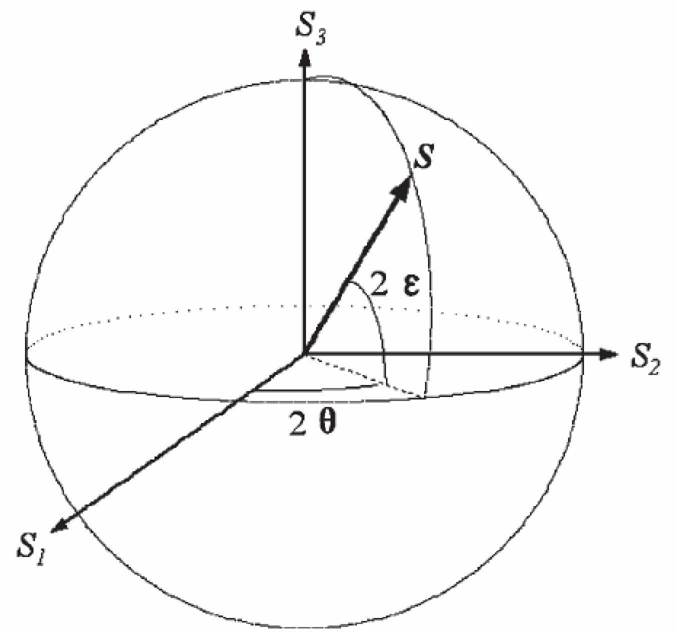
S_2 describes the amount of linear +45^o or -45^o polarization.

S_3 describes the amount of right or left circular polarization.

The Stokes parameters are expressed in terms of intensities and are easily measured using a polarization analyzer.
They can be displayed on the *Poincare sphere*.

θ polarization azimuth.

ε ellipticity angle.



SOA Mueller Matrix

The SOA Mueller matrix is composed of a *diattenuator* (as the TE and TM gains are not equal) followed by a *retarder* (phase shifter)*.

$$M = M_{dia} M_{ret}$$

$$M_{dia} = \frac{1}{2} \begin{pmatrix} G_{TE} + G_{TM} & G_{TE} - G_{TM} & 0 & 0 \\ G_{TE} - G_{TM} & G_{TE} + G_{TM} & 0 & 0 \\ 0 & 0 & 2\sqrt{G_{TE} G_{TM}} & 0 \\ 0 & 0 & 0 & 2\sqrt{G_{TE} G_{TM}} \end{pmatrix}$$

$$M_{ret} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\Delta\phi & \sin\Delta\phi \\ 0 & 0 & -\sin\Delta\phi & \cos\Delta\phi \end{pmatrix}$$

* L.Q. Guo and M.J. Connelly, *J. Lightwave Technol.*, 2007.

TE-TM Phase Shift

The TE-TM phase shift is given by

$$\Delta\phi = \frac{2\pi}{\lambda_{probe}} \int_0^L \left[N_{eff,TE}(z) - N_{eff,TM}(z) \right] dz$$

$N_{eff}(z)$ is the spatial and polarisation dependent *effective index*.

We can write

$$N_{eff,TE/TM}(z) = N_{eff,TE/TM,0}(z) + \frac{dN_{eff,TE/TM}(z)}{dN_1} \Delta N_{1,TE/TM}(n(z))$$

Active region refractive index.

$N_{eff,TE/TM,0}(z)$ is the effective index with no injected carriers. and was determined using Marcatili's method for rectangular dielectric waveguides*.

*S.H. Chuang, *Physics of Optoelectronic Devices,* Wiley, 1995.

Carrier Density induced Refractive Index Change

The change in the active region refractive index due to the injected carrier density is due to two main effects, *bandfilling* and *free-carrier absorption.*

$$\Delta N_{1,TE/TM}(n) = \Delta N_{bf,TE/TM}(n) + \Delta N_{fca}(n)$$

The change due to bandfilling is given by

$$\Delta N_{bf,TE/TM}(E) = \frac{2c\hbar}{e^2}\mathrm{PV}\int_0^\infty \frac{\alpha_{TE/TM}(E',n) - \alpha_{TE/TM}(E',0)}{E'^2 - E^2}\,dE'$$

where $\alpha_{TE/TM}(E,n)$ is the material absorption.

The index change due to FCA is usually given by

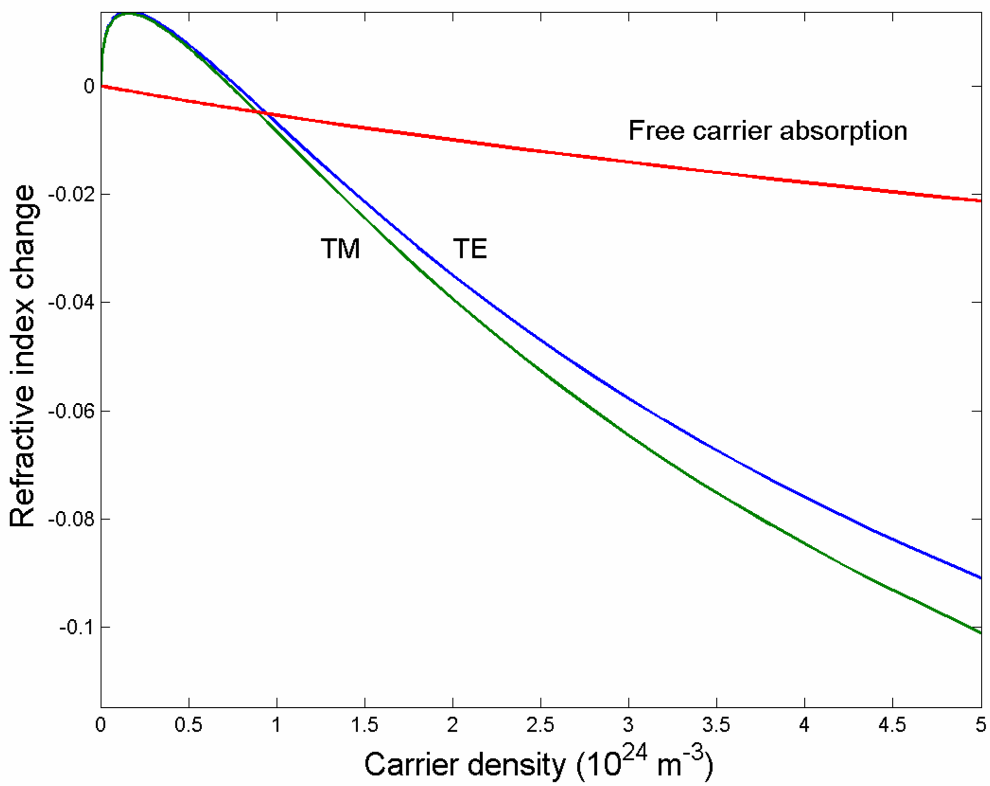
$$\Delta N_{fca}(n) = -\frac{e^2\hbar^2}{2N_1\varepsilon_0 E^2}\left(\frac{n}{m_c} + \frac{p}{m_v}\right)$$

This is not the case for a tensile-strained material, where the effective masses are not constant.

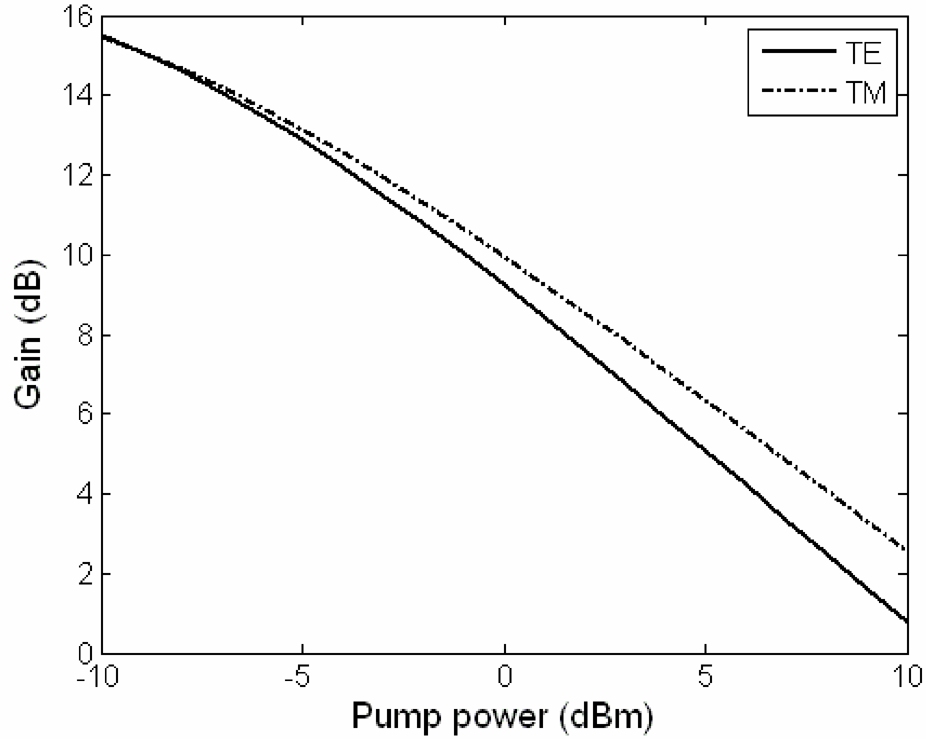
The conduction band contribution is given by

$$\Delta N_{fca,c}(n) = -\frac{e^2\hbar^2}{2N_1\varepsilon_0 E^2}\int_0^\infty \frac{k^2}{\pi^2 m_c(k)}\left[1+\exp\left(\frac{E_c(k)-E_{fc}}{kT}\right)\right]^{-1} dk$$

Slightly more complicated expressions are used for the contributions of the heavy- and light-hole valence bands.

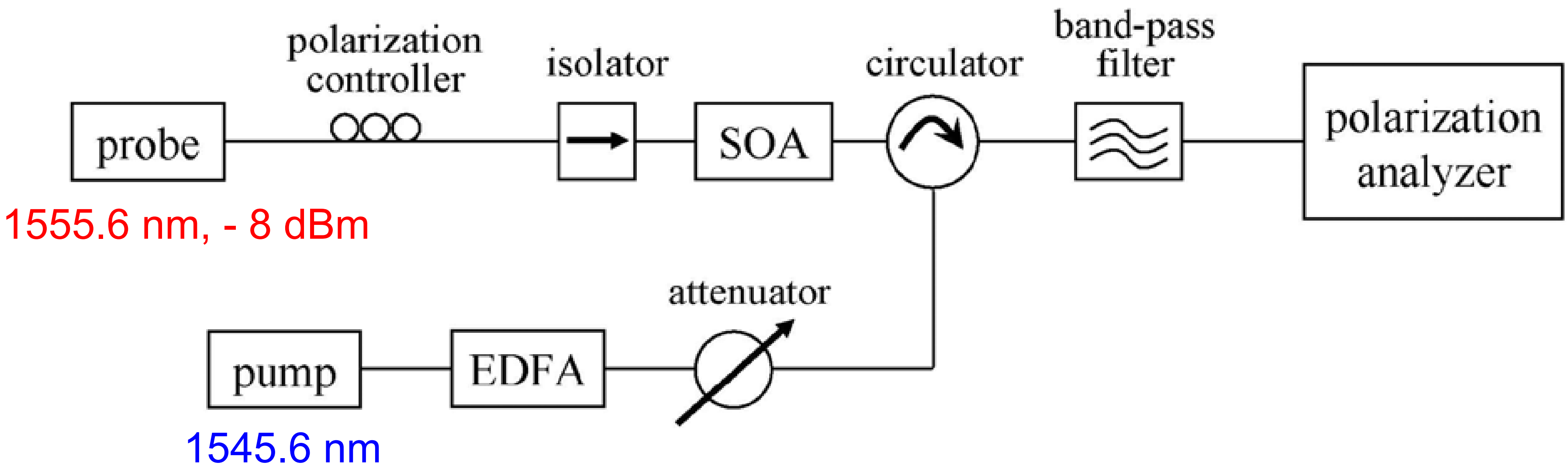


Active region refractive index change v.s. carrier density.



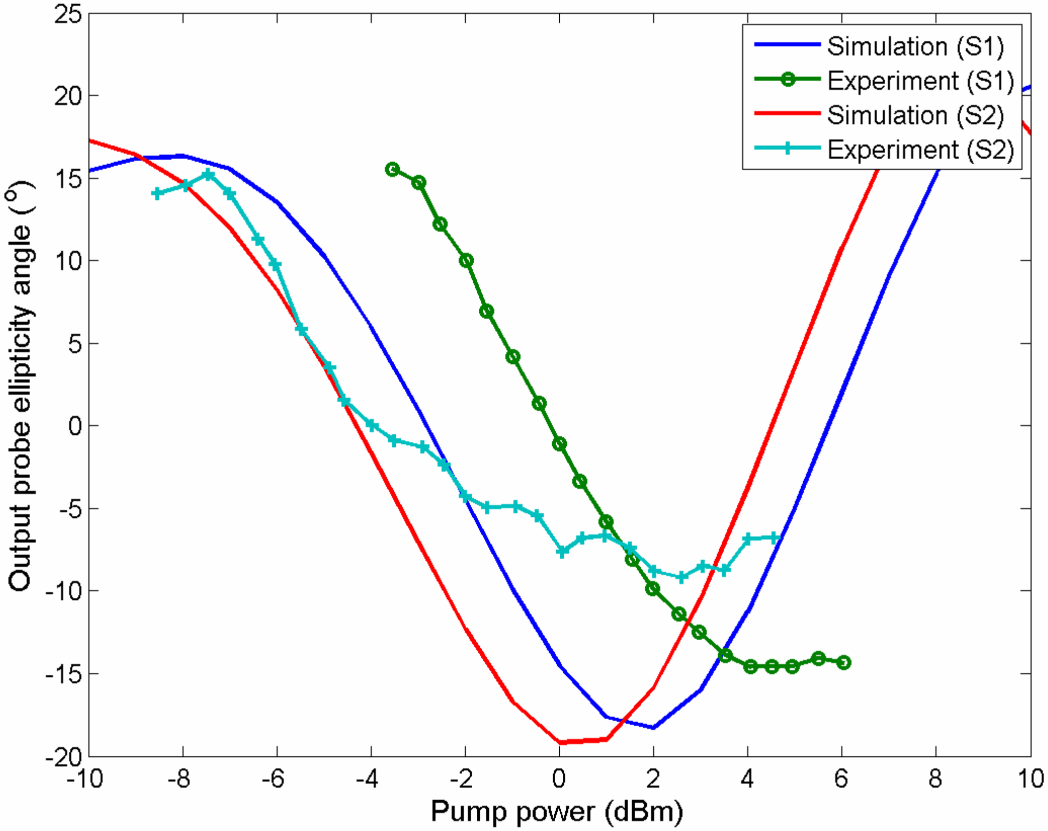
Simulated probe TE and TM gain versus pump power. Probe input power = -8 dBm.

Experiment and Simulations



Counter-propagating pump and probe.

Stokes vector of the output probe measured using a polarization analyzer.



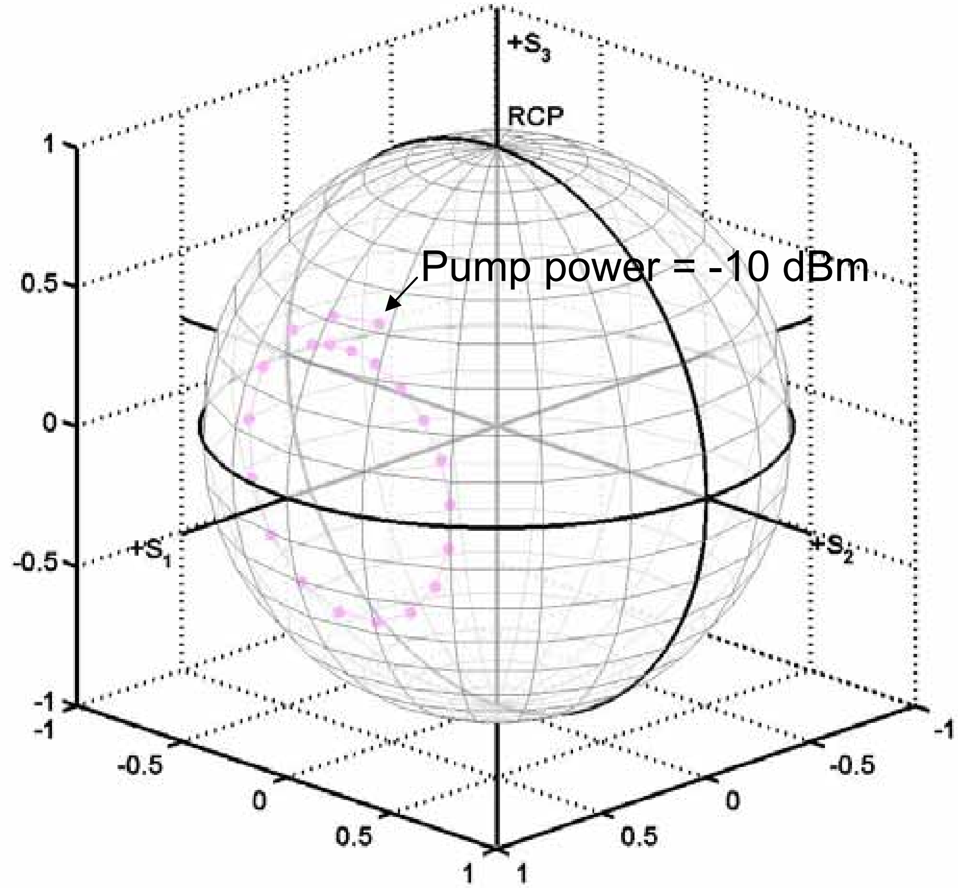
S1 = [1, 0.73, -0.46, 0.13]

S2 = [1, 0.75, -0.4, 0.37]

Ellipticity angle

$$\varepsilon = 0.5\tan^{-1}\left(\frac{S_3}{\sqrt{S_1^2 + S_2^2}}\right)$$

For pump powers between −7 and 7 dBm, the rolloff of the ellipticity-angle trajectories as predicted by the model are in good agreement with the experiment.



Evolution of probe polarization state shown on the Poincare sphere.

Possible discrepancies between experiment and simulation include.

- Uncertainty in pump and probe input powers and the actual proportion coupled to the waveguide TE and TM modes.
- Sensitivity of NPR experiments.
- Inaccuracies in estimation of TE and TM effective indices.

Conclusions

Developed a Mueller matrix technique for predicting NPR in an SOA, which uses no adjustable parameters.

Reasonably good agreement between experiment and simulations.

Future work will examine NPR for a wider range of input probe polarization conditions.