

Wafer and Chip-Level Optical Test

Solving Polarization Alignment with the IL/PDL Test System

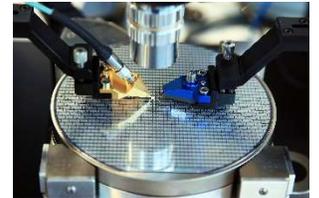
Semiconductor Technology for Photonic Integrated Circuits

Photonic integrated circuit (PIC) and silicon photonics technologies are being used to manufacture devices for optical communications at higher volumes with lower costs, energy consumption, and size. This is now especially driven by the rapidly increasing needs of data centers. These technologies also offer the means to realize new functionality with high-level integration of electronics and optics.

Like in the semiconductor electronics industry, appropriate test and measurement at an early stage, like wafer-level test, is valuable to avoid the high cost of processing and packaging substandard devices that will fail final test as well as for control and diagnostics of the wafer production process. Typically this involves parametric tests to characterize the material and structuring quality, like measuring sheet resistance and capacitance electrically and attenuation and responsivity optically. Optical testing generally also includes the dependence on wavelength and on the alignment of optical polarization with the waveguide structures. For transponder devices like photodetectors and modulators, the RF-frequency dependence is also important for characterizing the bandwidth of the devices.

The Challenge of Polarization Alignment

Adding optical measurements to wafer-level test requires optical probes to couple light to or from the wafer. Optical fiber cable is the usual way to connect to the instruments. Standard single-mode fiber (SMF) has a nominal core diameter of 9 μm , which is significantly larger than typical waveguide dimensions on the semiconductor wafer, where the higher refractive index results in shorter wavelengths and stronger confinement of the intensity profile. Also the waveguides typically have a rectangular cross-section, while the fiber core is round. Therefore, an adapting structure is needed to provide matched coupling between the probe fiber and the wafer waveguides. For example, coupling into the surface of a wafer to waveguides running parallel to the wafer surface is achieved with coupler grating structures that can match the beam profiles and provide the refraction needed to change the direction of the light. Tapered waveguides can be used for edge-coupling into chips after dicing the wafer. For packaging, the chips can be attached to an interposer, generally a passive planar structure that provides accessible connections to the smaller chip.



Silicon photonics is widely used as a label for the technology to produce devices on wafers that combine optical and electrical functionality. Other semiconductor materials, especially InP, are also used. Bringing optical functions together with highly integrated CMOS devices is an attraction to silicon.

In all of these cases, it is common for the coupling efficiency to depend strongly on the alignment of the optical polarization, due to the properties of both the waveguides and especially of the coupling gratings. This makes it important to either assure that the light is aligned with the correct axis of the waveguide or to measure the dependence of the device parameters on polarization. For typical planar waveguides with rectangular cross-section, the polarization modes associated with the axes are commonly labeled transverse electric (TE) for electric field of the optical wave along the wider dimension usually parallel to the wafer surface and transverse magnetic (TM) when the magnetic field is parallel to the wide dimension. The two polarization modes are orthogonal.

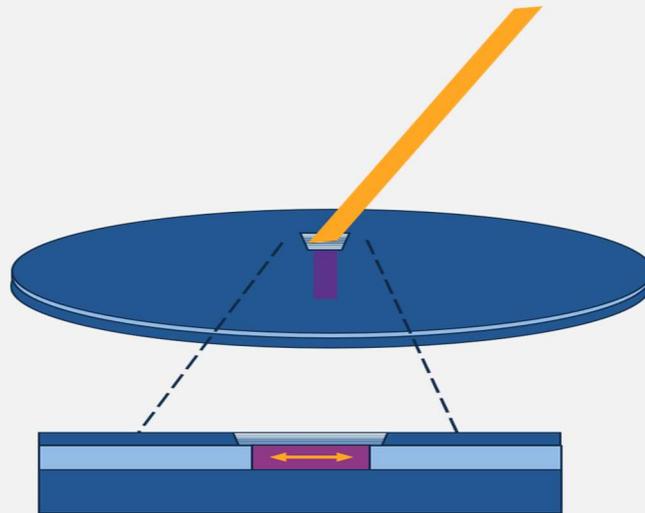


Figure 1: Illustration for coupling light from an optical probe into a wafer waveguide structure through a surface grating. The arrow indicates the electric field direction for TE polarization.

One way to assure alignment is using polarization-maintaining fiber (PMF), which has structure to define optical axes so that when the input light is exactly aligned with either axis the output light will also be aligned with that axis. This can be used if the laser source provides the output aligned in PMF and the alignment of the probe fiber axis with the wafer axis can be assured. It can be a good approach, but is limited in flexibility. Such probes can only be easily used for measuring with that one state of polarization but not for determining polarization dependence. And any intermediate instruments or components, like an optical attenuator or switch or coupler must also be a polarization-maintaining device. Every connection to PMF is also subject to some misalignment that increases the crosstalk between the modes and degrades the measurements.

Another approach uses SMF probes with a polarization controller before the probe. The output signal from the device under test (DUT), either electrical or optical, is optimized by adjusting the polarization controller. In this way, when the laser source is stable, the polarization at the DUT can be aligned. Unfortunately, the polarization at the output of the polarization controller and the SMF probe generally varies with the wavelength of the light. So if the device parameter (like attenuation or responsivity) should be determined over a wide wavelength range it is usually necessary to repeat the optimization step at several wavelengths over the desired range. This prevents getting good measurements of a particular axis by simply scanning the wavelength of the tunable laser while sampling the DUT output. Typical

results show an optimum signal at the wavelength used for alignment and (falsely) degraded performance as the wavelength is increasingly far from this point. An example of this is shown in Figure 2 (blue curve) for a measurement of a polarization filter. The severity of degradation depends on the wavelength dependence and on the amount of birefringence in the polarization controller, fibers and other instruments in the optical path. Breaking the sweep into shorter separately optimized segments to avoid this requires much longer test duration.

Single-sweep Measurement with Matrix Analysis

An improved approach, especially for obtaining wavelength-dependent data, is provided by the tunable-laser based systems controlled by the N7700A IL/PDL software engine. This approach measures the complete polarization dependence with a single wavelength scan. The results can be used to provide the response (insertion loss or responsivity) averaged over all possible polarization states, the dependence on polarization, and the response for the preferred polarization state, without needing to first optimize the polarization and especially without needing to maintain the optimization vs. wavelength. Such a result is shown as the red curve in Fig. 2.

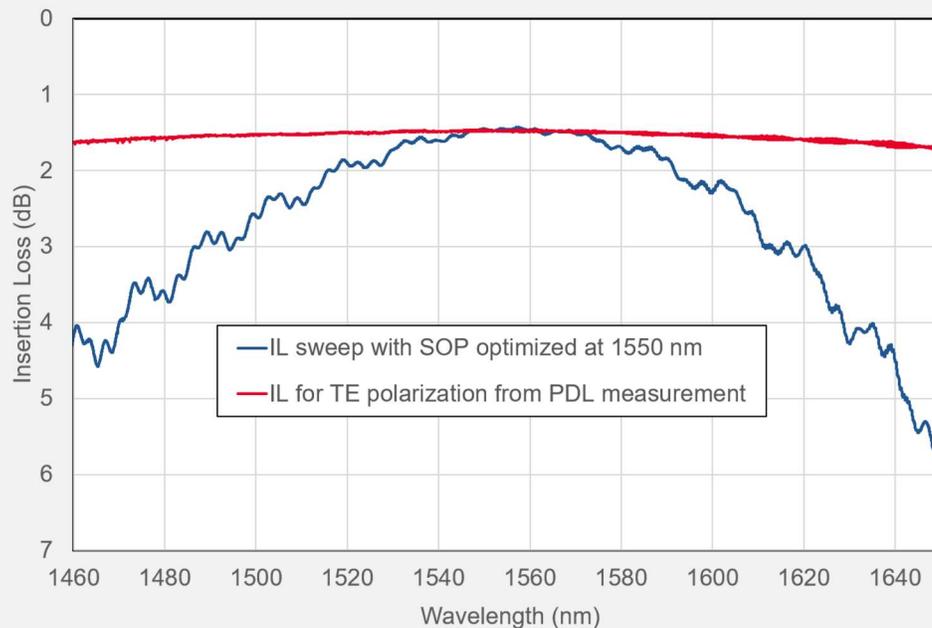


Figure 2: Insertion loss measurements of a polarizer; blue: using the polarization controller to align the polarization at 1550 nm, red: using the matrix measurement to calculate the IL at the aligned polarization.

The measurement itself uses the fast-switching N7786B polarization synthesizer to repeatedly step through a set of 6 states of polarization (SOP) while the laser scans the wavelength continuously at a fixed sweep speed. The setup can thus measure the output signal for each 6-SOP sequence in just 300 μ s. This makes the measurement very insensitive to vibrations and drift that can distort the relative orientation of the SOPs to each other when they are separated by longer times, like the time between separate wavelength scans for each SOP.

After the sweep, the measured wavelengths, SOPs, and output signal levels, all logged in real time by the respective instrument, are uploaded and used to determine the Mueller matrix elements needed to calculate the polarization dependence of the signal power through the DUT. Besides the conventional analysis for polarization-averaged IL and PDL, the software also provides the IL spectra corresponding to the optical axes of the DUT, presenting these as the TE and TM pair. The software does not have enough information from the measurement to determine which spectrum is assigned to TE and which to TM, so this labeling is arbitrary, but can often be correctly assigned with knowledge of the expected DUT characteristics. In some cases, the TE and TM spectra can cross, so this analysis is not identical with the spectra for maximum and minimum response. The TE/TM analysis does depend on the assumption that the polarization dependence in the measurement is predominantly caused by the difference between the DUT axes.

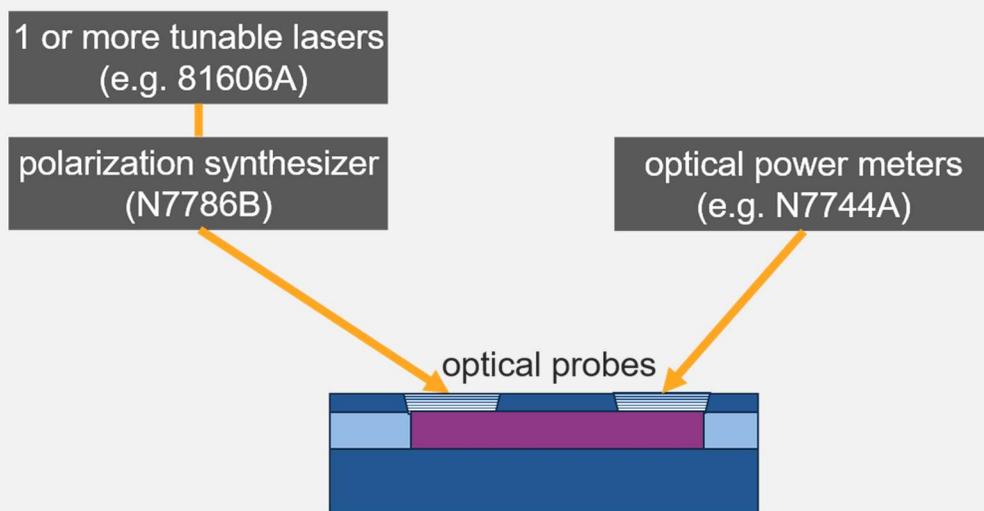


Figure 3: Basic instrumentation for the single-sweep matrix measurement with the N7700A IL/PDL software. For details, see www.keysight.com/find/n7700

So with this approach, the wavelength-dependent measurement can be made as soon as the probes have been positioned, without first needing to align the polarization and without working around its drift with wavelength. That both saves time and improves measurement quality. Another example of the TE/TM result directly from a measurement is shown in Fig. 4, with a DUT where the TE and TM spectra cross (many times!).

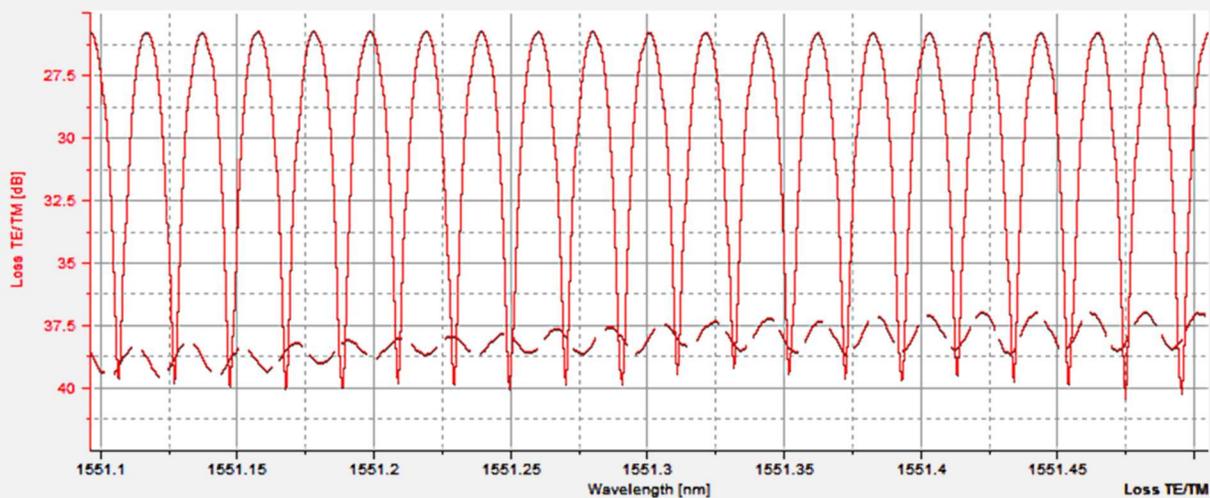


Figure 4: Insertion loss spectra for the TE and TM polarization modes of a photonic integrated circuit, determined from the single-sweep matrix measurement.

Static Mode

The above condition, “as soon as the probes have been positioned”, points to another polarization aspect. It can still be necessary to provide an optical input signal and align the SOP with the DUT for other operations, including probe positioning, adjusting settings to the DUT, and measuring the dependence of the DUT to other variables such as modulation frequency, temperature or applied voltages. These operations are supported by the ‘Static Mode’ functionality of the N7700A IL/PDL engine.

The ‘Static Mode’ provides functions from the IL/PDL engine server to set the polarization synthesizer to output a chosen SOP with a chosen laser wavelength and power. This can be done from the client GUI or from an automation program. With these settings, the desired operations can then be performed using the optical power meters or other instruments. When that is finished, the IL/PDL software can again be used to change to a different static setting or to make swept-wavelength spectral measurements.

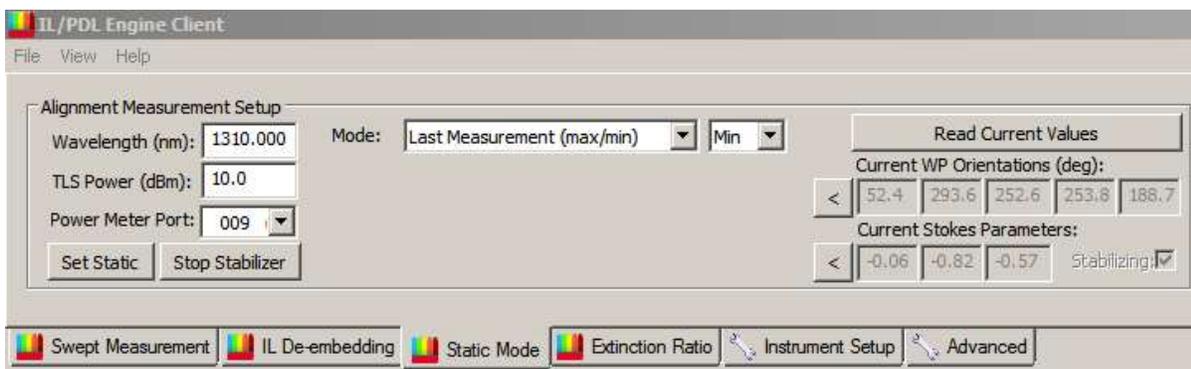


Figure 5: Static Mode tab of IL/PDL Engine Client.

The choice of SOP can be made in several ways. The Stokes vector values can be set directly at the N7786B, which has a built-in polarimeter sampling the output signal. So if a desired SOP is known, it can be easily reproduced this way, and the corresponding orthogonal SOP can also be selected. Similarly, the internal equivalent waveplate settings can be used to reproduce settings.

But the SOP that is incident at the probe tip or DUT is not initially known because the relation between the SOP at the input and output of the SMF from the N7786B to the probe is not permanent, but can change with temperature, fiber movement, wavelength and other factors as well. Therefore, the Static Mode can also determine and set the SOP based on the matrix analysis of a previous swept-wavelength IL/PDL measurement, either directly after that measurement or based on a saved measurement file. This is very powerful because it uses the single-sweep matrix result to identify the N7786B settings that produce the desired SOP at the DUT.

As a use case example, the following steps could be used.

1. An initial positioning of the probes is made, sufficient to couple light into the DUT and receive the output signal.
2. With this, the single-sweep IL/PDL measurement is made over the chosen wavelength range.
3. From the result, a wavelength where the signal transmission is reasonably high, like in a passband, can be chosen. On the Static Mode tab, this wavelength can be entered and the Mode setting “Last measurement (max/min)” chosen to use the polarization setting for the maximum (or minimum) signal level at this wavelength from the chosen detector port. Pressing “Set Static” then adjusts the laser and polarization controller to these settings.
4. The probe positions can be further optimized, using only signal polarization in the desired waveguide axis.
5. When finished, the IL/PDL engine can again be used in Swept Measurement mode with the optimized connections.

While still in Static Mode, the stabilizer function of the N7786B continues to regulate the output SOP, so that it can be kept constant if the SOP input to the N7786B changes. This function uses a small modulation of the SOP to provide feedback. If this interferes with the operation it can be stopped and the N7786B remains fixed at the current waveplate settings. It is not necessary to first press “Stop Stabilizer”, before running a swept measurement.

In some cases, the desired wavelength for the static mode operation may not be the best for identifying the polarization axes of the DUT. Consider for example a wavelength filter for which the center wavelength of the passband is offset between the TE and the TM mode. This can result in a crossing of the TE and TM spectra near the center of the passband, where the static operation should be performed, as shown in Fig. 6. At this crossing point, the SOP cannot be defined by the maximum or minimum level. For this case the Mode setting for “Last measurement (PDL PSP)” can be used. This then uses the SOPs corresponding to the TE/TM analysis of the swept measurement, which identifies the axes at a wavelength where this is most evident. The choice between the two axes can be selected as PSP1 or PSP2, as abbreviations for principal states of polarization from the PDL analysis.

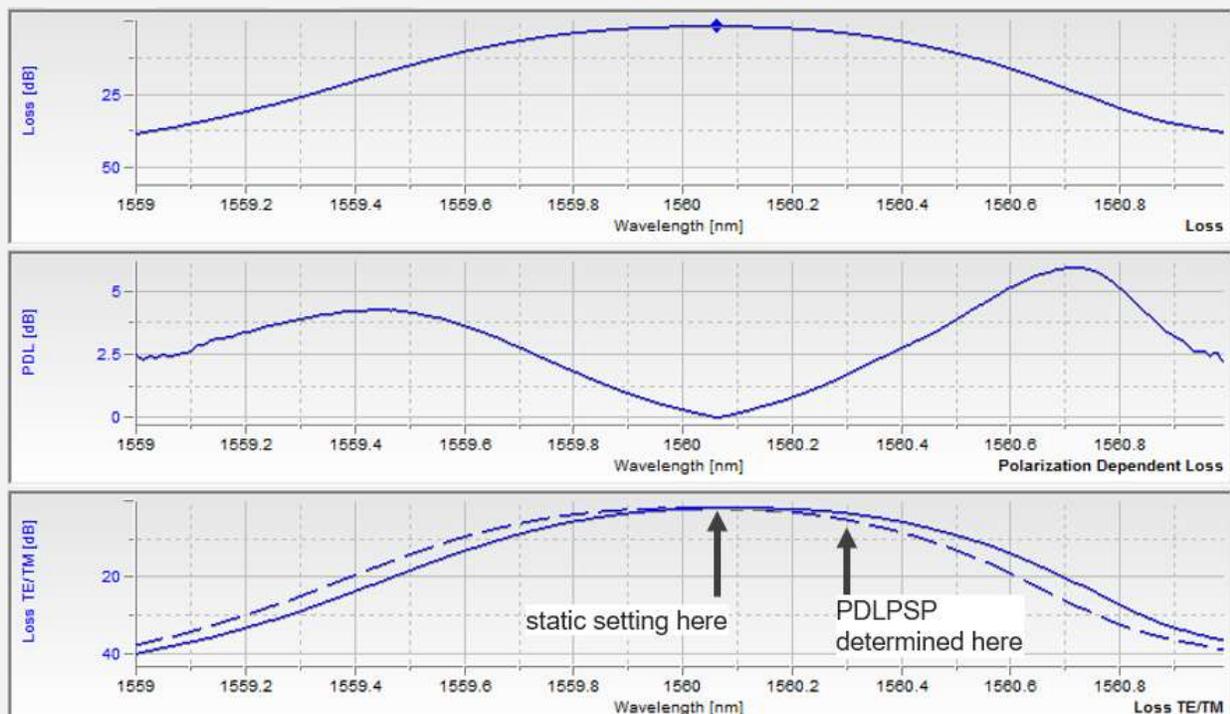


Figure 6: Measurement curves illustrating a case for using the PDLPSP setting to determine the SOP.

The mode setting can also be chosen to use a saved measurement file rather than the last measurement. That is especially useful if one device on the wafer has a clear axis assignment, which is not so clear on other devices. It is also helpful when measurements are to be performed in multiple sessions between which the IL/PDL engine is closed. Of course, this setting is only useful as long as the relationship between the SOP at the N7786B and the DUT remains stable.

SOP Stabilizer

As mentioned above, the Static Mode starts active stabilization of the SOP with the N7786B (unless the Mode is set to use fixed waveplate values). This can be very useful because it permits switching the input of the N7786B to another optical source and can then align the polarization of that source with the DUT axes, based on the previous matrix analysis.

An example relevant for parametric testing on wafers is illustrated in Fig.7. An optical switch is used to select either the tunable laser or the N4373E Lightwave Component Analyzer (LCA) as optical source to the N7786B. The LCA is used to measure the RF frequency dependence of device responsivity, especially for optical-to-electrical and electrical-to-optical transponders. In the former case, a modulated optical signal is applied to the DUT.

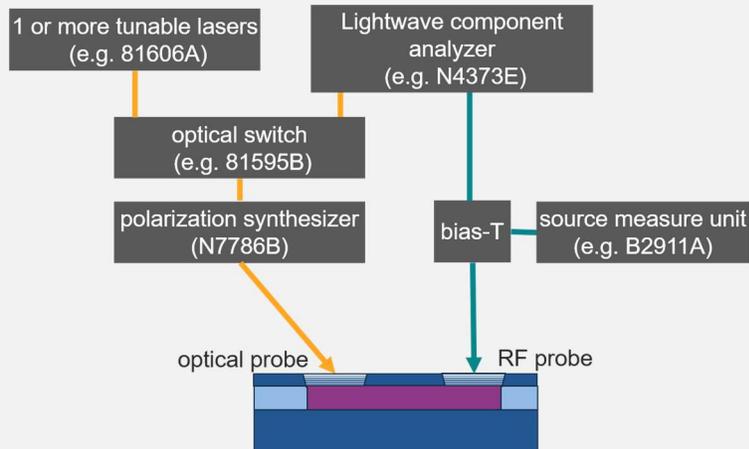


Figure 7: Example setup using the matrix measurement to set and stabilize the polarization, also for applying the modulated optical signal from the LCA.

Using the illustrated layout, the wavelength dependent CW responsivity of such a device can be measured with the swept-wavelength measurement, also resolving the spectra for TE and TM polarization. In this case the electrical photocurrent output is measured with a source/measure unit in place of the optical power meter. Then the Static Mode can be used to align the N7786B output SOP for the wavelength to be used by the LCA transmitter so that when the input of the N7786B is switched to the LCA, the SOP of the modulated optical signal is transformed to that same SOP. As in other static mode cases, this depends on stability of the optical path between the polarization controller and the wafer. The LCA software also includes functionality to de-embed the attenuation and delay from the additional elements in the optical path as well as the RF probes. See application notes 4989-7808EN and 4989-9136EN for further details.

www.keysight.com/find/lca

Additional Literature

For additional details on the N7700A IL/PDL software, please refer to the documents at www.keysight.com/find/n7700.

Learn more at: www.keysight.com

For more information on Keysight Technologies' products, applications or services, please contact your local Keysight office. The complete list is available at: www.keysight.com/find/contactus

