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Thin film lithium niobate optical modulators for THz frequency applications

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ABSTRACT

Thin film lithium niobate optical modulators allow modulation of optical signals up to several THz due to perfect phase matching between RF signal and optical signal that can be achieved using thin film devices. The platform uses a ridge waveguide fabricated by direct etching of lithium niobate thin film fabricated on silicon substrates. The lithium niobate thin film has been developed and optimized in our facility. Transmission spectrum of fabricated micro-ring resonators on this platform shows a linewidth of approximately 7 pm corresponding to a Q value of 2.2×10^5 and an optical waveguide loss of 2 dB/cm. A coupling loss of -5 dB per coupler is obtained using grating couplers. Measured fiber to fiber insertion loss of the device is -10 dB. The measured 3-dB optical bandwidth of the fiber to fiber optical coupler is 45 nm. A Mach-Zehnder modulator consisting of two MMIs and 6 mm long arms were designed and fabricated on X-cut thin film of lithium niobate. Measured V_π of the device is 7.5 V at low frequencies (i.e. 10KHz) for a device with 7 µm gap between the electrodes. The measured half-wave voltage-length product, V_π.L, is equal to ~4.5 V.cm. High speed measurement results of the device response are presented. A THz electric field of 10kV/mHz$^{0.5}$ is detected with a low dynamic range OSA and it is estimated that a THz electric field with a strength as low as ~100V/mHz$^{0.5}$ is detectable by modulating the optical signal using these modulators.

Keywords: Optical modulator, Terahertz, RF photonic, Lithium niobate, Thin film, Mach-Zehnder modulator

1. INTRODUCTION

The THz (Terahertz) frequency range covers the electromagnetic spectrum in the range of 0.1THz to 10 THz and is a range of frequencies that is currently highly researched. THz wave photons have unique characteristics that allows them to be used in a variety of applications. THz signal can penetrate many materials where optical signals cannot penetrate and hence, they can be used to see inside opaque materials. This has for example applications in security. Another application for THz waves is in detection of molecules. Air pollution monitoring system need low cost THz gas spectroscopic tools that monitor air quality and detect pollutants. As data rates in wireless communication systems increase, it is required to use higher carrier frequencies which approach the THz frequency range. All of these applications require signal characterization in THz frequency range.

In order to characterize THz wave signals, the best approach is conversion of THz wave signals to photonic signals and using the optical signal characterization tools. A key component of any THz photonic signal processing system is an optical modulator that can modulate optical signals at THz frequencies. We have developed a modulator technology that can be used to modulate optical signal at THz frequencies. Our technology allows to make optical modulators that can be used to modulate optical carrier signals in THz frequency range. Once the THz wave signal is converted to optical frequency, photonic signal processing functions can be performed in optical domain. With our proposed device all the benefits of photonic technology can be leveraged for THz wave signal processing applications.

1.1 Modulation bandwidth

The key enabling technology for THz frequency modulation is thin film lithium niobate technology that Partow is developing[1]. Using thin film lithium niobate, it is possible to perfectly phase match the THz wave signal and the optical signal and achieving modulation speeds up to several tens of THz is practical[2]. The phase matching is possible since the effective index for THz signal (due to its very long wavelength) is not affected by the submicron thick lithium niobate thin films. The THz wave signal effective index and is almost equal to the SiO_2 (or quartz substrate) refractive index.

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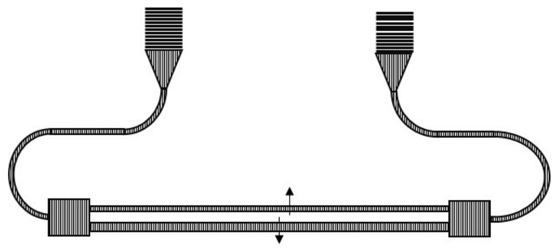
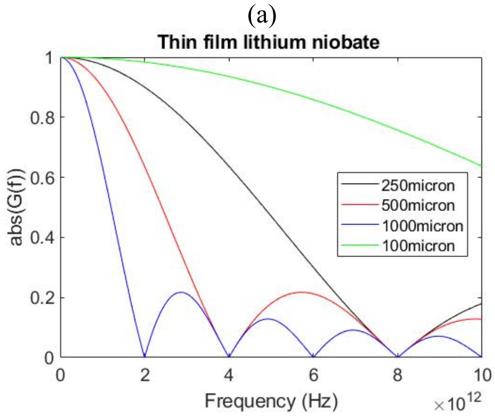
The refractive index of quartz is ~2 at THz frequencies. On the other hand, for the optical signal due to its small wavelength (i.e. 1.55 microns) the effective refractive index of the guided mode is close to lithium niobate optical refractive index and is also approximately equal to ~2. Hence it become possible to phase match the THz signal and the optical signal in thin film lithium niobate waveguides modulators. Figure 1(a) shows the structure for our modulators. The modulator consists of an input and an output grating coupler to couple light between an optical fiber and the thin film modulator devices and a Mach-Zehnder modulator section where two arms are used. If free space THz wave signals are used for modulation, one arm can be poled to reverse the direction of spontaneous polarization of lithium niobate crystal to achieve opposite refractive index change for a given electric field and hence intensity modulation in the output. Alternatively, if metallic electrode is used, poling is not required, and the electric field will be reversed for one arm compared to the second arm. Figure 1(b) shows calculated modulation bandwidth for a typical thin film lithium niobate devices for different arm lengths. As it can be seen modulation bandwidth of several THz is possible with these devices. Further increase in device bandwidth is possible by designing the waveguide structure to achieve better phase matching,



(a)



(b)

Figure 1. (a) Schematic of the Partow THz modulator device, (b) Calculated modulation bandwidth for thin film lithium niobate modulators with different length for device arms.

2. FABRICATION PROCESS AND BASIC CHARACTERIZATION

2.1 Fabrication Process

Our thin film fabrication technology is based on transferring crystal ion sliced thin layer of lithium niobate on silicon or quartz substrates. Our technique uses ion implantation, wafer bonding and crystal ion slicing to achieve single crystalline thin film of lithium niobite. The thin films produced using this method are single crystalline and their optical and electro-optic properties are identical to bulk single crystalline crystals.

Figure 2 shows the fabrication flow for our optical modulators based on lithium niobate thin film platform[3]. A ridge waveguide is formed by dry etching of either deposited SiN or directly etching of LN. For experimental results in this paper, we have used the hybrid SiN-LN waveguide structure. After forming the MESA structure, a polymer layer is coated and then etched in electrode locations. The RF electrodes are finally formed by lift-off process. The waveguide structure consists of a thin layer of lithium niobate core region, a silicon dioxide (SiO_2) bottom cladding, and an index matching rib region (in this case silicon nitride).

The simulation results for the performance of waveguides, MMI couplers and grating couplers demonstrate that a hybrid platform consisting of 300nm SiN rib layer on top of 300nm LN layer is the best for the electro-optic sampling of THz signal. The experimental results demonstrated in the next section are based on this waveguide platform.

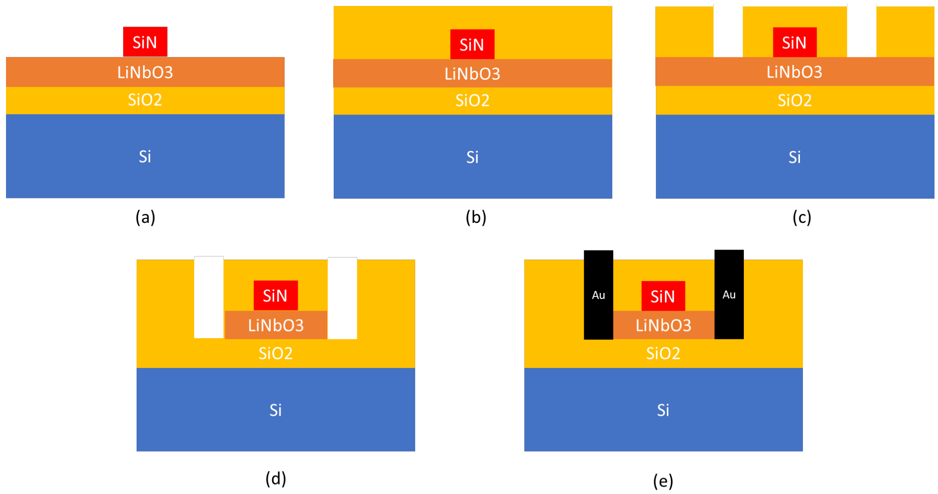


Figure 2. Fabrication flow for Partow's invented high-index contrast thin film lithium niobate hybrid waveguide.

The device layout and the fabricated device are shown in Figure 3. The light is coupled into to waveguide from fiber using a grating coupler designed for TE mode. The coupled light to chip is equally divided between two arms of Mach-Zehnder modulator using a MMI coupler. The length of each arm in MZ interferometer is 6mm. Then, the lights in two arms of MZ combine again using MMI coupler and couple to output fiber using second grating coupler. The total length and width of the diced device is 6.5mm and 0.7mm, respectively. The layout in Figure 3 was written using e-beam lithography and the pattern is transferred into our hybrid SiN/LN platform with RIE/ICP etch. The layout in Figure 3 also shows the modulation electrodes that carry the RF signal.

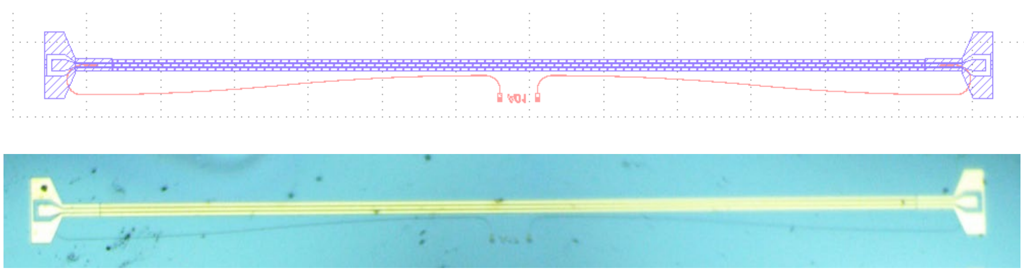
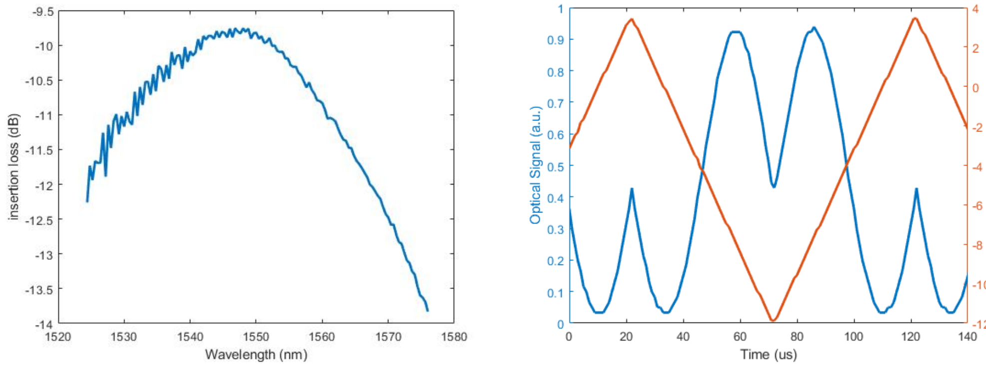


Figure 3. The layout of the MZ modulator and the image for the fabricated and diced chip.

2.2 Low-frequency characterization

Figure 4(a) shows the measured insertion loss versus wavelength after the light has passed through the two grating couplers (i.e., fiber-to-fiber insertion loss). We achieved less than -10 dB insertion loss for our grating couplers. Considering that the propagation loss between the input and output couplers in a waveguide less than one-millimeter-long is negligible, a coupling loss of ~ 5 dB is extracted per coupler. The measured 3-dB fiber to fiber bandwidth of the coupler is 45 nm. Based on theoretical calculation -4dB loss per couplers is expected.



(a) *(b)*

Figure 4. (a) Measured Insertion Loss for the Grating Coupler (after passing two input and output couplers). (b) Response of a MZM with a 7μm electrode gap – the orange triangular waveform is the applied voltage and the blue curve is the observed modulation. Both electrodes are 6 mm long

We have characterized the fabricated devices by applying a sawtooth modulation voltage around 10 kHz. Figure 4(b) shows the applied low-frequency electrical signal and the measured optical modulation signal for a device with 7 μm gap between the electrodes. As can be seen in Figure 4(b), the V_π of the device is 7.5 V. Since the electrodes are 6 mm long, the measured half-wave voltage-length product, V_π.L, is equal to ~ 4.5 V.cm. An extinction ratio (ER) of approximately 24 dB is measured in the modulator.

3. HIGH SPEED MODULATION CHARACTERIZATION

Figure 5 shows a schematic of the experimental setup. The tunable C-band laser (Pure Photonics PPCL100) is operated at 1550nm (193.5THz) with 13.5dBm (22.4mW) maximum optical power. The fiber polarization controller (ThorLabs FPC560) is a manual paddle-style controller, adjusted to provide a vertically polarized beam [1]. The optical spectrum analyzer (ID-Photonics ID-OSA-MPD-00) scans the C-band at 1Hz with 1.7GHz resolution bandwidth and 312.5MHz sampling interval. The dynamic range for the OSA is 45dB. Two MZI devices were tested with measured optical insertion losses of 17dB and 14dB. The RF signal generator (Agilent 8257D) is used to generate frequencies between 1-20GHz with 14dBm (25mW) maximum output power. A bias-tee (Anritsu K250) is used to apply a DC bias to the RF signal. The RF signal is fed into an RF amplifier (Mini Circuits ZVA-213-S+) with 26dB gain (P1dB = 24dBm). Gain flattening is applied during frequency-dependent measurements to maintain a constant 20dBm (100mW) output power across the 1-20GHz range. The RF signal is coupled to the MZI using a microprobe (Form- Factor/Cascade ACP40-L-GSG-150) with 0.6dB typical insertion loss.

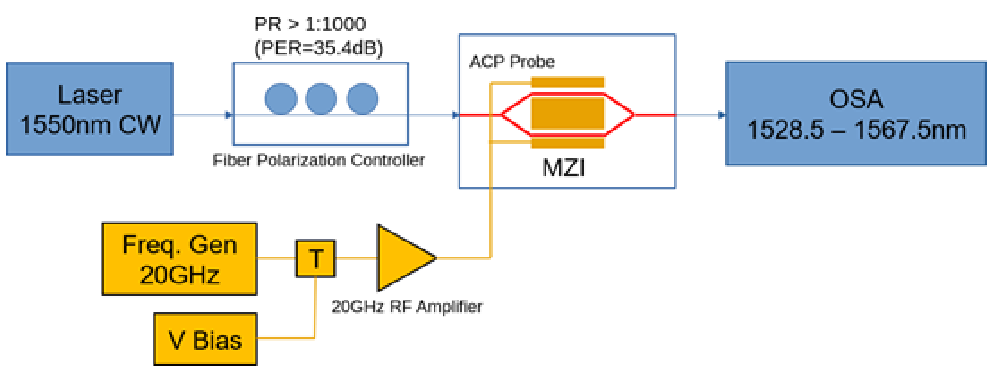


Figure 5. A schematic of the experimental setup used for optical sideband characterization.

RF impedance matching and insertion loss are measured via scattering parameter characterization using a vector network analyzer (Anritsu 37397C) with 65GHz bandwidth calibrated using a standard SOLT procedure. A second, identical microprobe (FormFactor/Cascade ACP40-L-GSG-150) is also used for this characterization.

In Figure 6, experimental results of optical sideband generation at RF modulation frequencies of 10GHz and 15GHz, 24dBm and 20dBm RF power respectively, are compared with simulations of the expected results. Modulation index values are estimated from experimental data using the power difference between the carrier band and the first order sideband. The simulation results illustrate the expected number of sidebands to be observed in the experiment taking into account the available optical laser and RF power, known optical and co-planar waveguide characteristics, optical and RF insertion losses, as well as the sensitivity of the optical spectrum analyzer (OSA).

The carrier wave frequency and optical power measured with the OSA agree well with the expected values. The frequencies observed for the optical sidebands also agree well with the modulation frequencies of 10 GHz and 15 GHz, respectively. The measured line width of the carrier wave and sidebands is limited by the 1.7GHz frequency resolution bandwidth of the OSA. The amplitudes of the first order optical sidebands are reduced compared to the expected amplitudes by 6.1dB at 10GHz and 0.1dB at 15GHz.

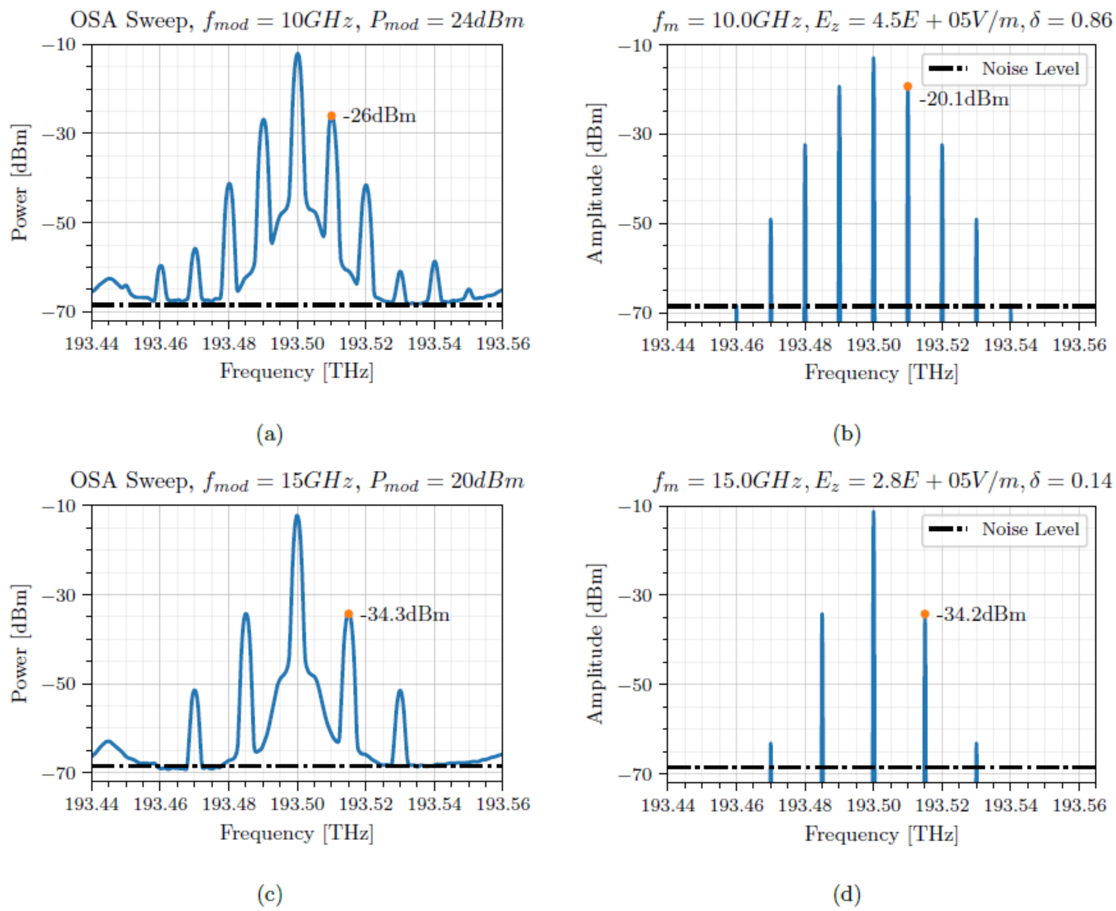


Figure 6. Experimental sideband generation (a,c) compared to simulated sideband generation (b,d) at fRF = 10GHz and 15GHz with PRF = 24dBm and 20dBm, respectively. First sideband amplitude is marked as a point of reference.

Scattering parameters were measured using a vector network analyzer to determine RF impedance matching and insertion loss. Figure 7 shows the RF impedance matching (S_{11}) and insertion loss (S_{21}) over a 1−50GHz range. S_{11} is less than -10dB over the entire frequency range, indicating good impedance matching to 50Ω. RF insertion loss shows a sharp increase near approximately 16GHz.

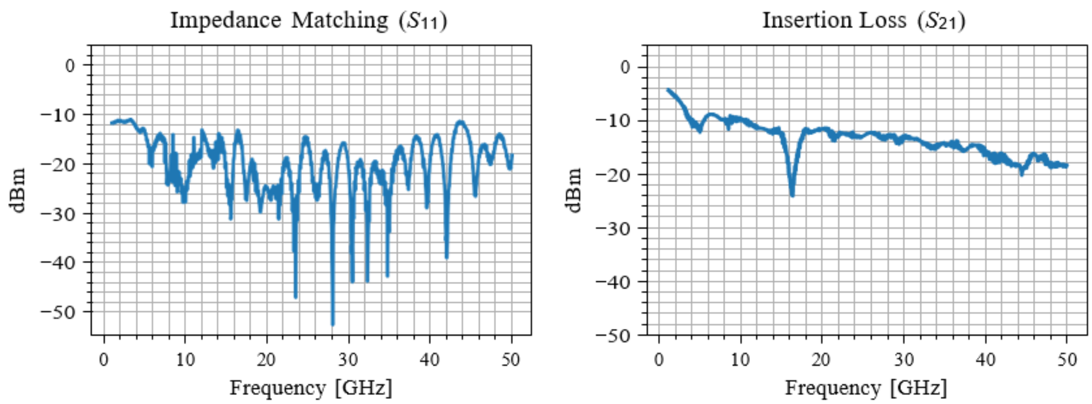


Figure 7. RF impedance matching and insertion loss for Partow's device.

Minimum RF power to produce detectable sidebands is measured by sweeping RF power at three frequencies (10GHz, 15GHz, and 20GHz). A detectable sideband is defined as a sideband with an optical signal-to-noise ratio (OSNR) greater than 3dB (with 70dBm noise floor). Figure 8 shows the results of this characterization. The device shows good RF power sensitivity; power levels as low as -14.3dBm at 15GHz produce reliable sideband detection (Table 1). This is equal to an electric field sensitivity value of approximately 10,000V/mHz$^{0.5}$ assuming the gap between the electrodes of the device is 6microns and a 50ohm impedance value Using an spectrometer with a better dynamic range of 70dB and lower RF signal loss in the device it is expected that RF power level as low as -55dBm can produce a detectable signal and hence electric field values as low as ~100V/mHz$^{0.5}$ is detectable with our current devices.

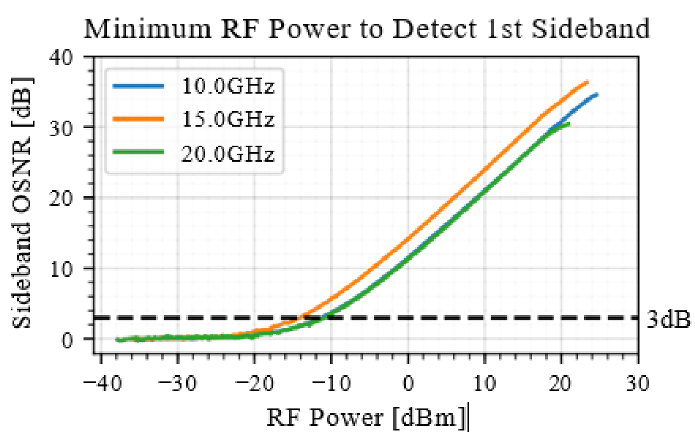


Figure 8. RF power dependence of first sideband amplitude at 10GHz, 15GHz, and 20GHz.

Table1: RF power detection thresholds.

Frequency	Min. Power
$10GHz$	$-11.3dBm$
$15GHz$	$-14.3dBm$
$20GHz$	$-10.8dBm$

4. CONCLUSION

An electro-optical modulator based on thin film lithium niobate has been designed, fabricated and characterized. The platform includes a thin layer of lithium niobate core region, a silicon dioxide bottom cladding, and a silicon nitride rib region. Each of grating couplers used to couple light in and out of modulator has 5 dB insertion loss with 90 nm bandwidth. The half-wave voltage of the 6mm long modulator with gap of 0.7 micron is 7.4 V. Extinction ratio (ER) of approximately ~24 dB is measured for the modulator device. We have studied the DC drift of electro-optical modulator device. High speed measurement of device response shows that a THz electric field of $10kV/mHz^{0.5}$ is detectable with a low cost OSA. Based on the results, we predict that a THz field with a strength as low as $\sim 100V/mHz^{0.5}$ is detectable by modulating the optical signal using these modulators and by detecting the modulated optical signal using a better optical spectrum analyzer.

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