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50-GHz Bandwidth, 0.75-A/W, Optoelectronic Stimulus Probe Head Employing Multimode Waveguide p–i–n Photodiode

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***Abstract*— We developed a highly efficient, broad-band optoelectronic stimulus probe head employing a 1.55-μm waveguide p–i–n photodiode (WGPD). The novel multimode waveguide structure of the WGPD and optical lens-based rigid coupling assembly yielded a very high responsivity of 0.75 A/W. The OE probe has an effective 3-dB bandwidth of 50 GHz which is currently limited by the frequency dispersion of the CPW used in the probe. 2-mW, 64-Gb/s RZ optical pulse patterns were successfully able to be converted to 200 mVpp electrical pulses.**

I. Introduction

Optoelectronic techniques are the most promising methods to characterize ultra-broad-band electronic devices. To achieve large-signal pulse pattern responses, which can be measured at real operating bit rates in devices near 100-Gb/s, highly efficient optical to electrical conversion probes with flat broad-band response are essential as well as ultra-high bit-rate optical pulse pattern generators [1]. Recently, picosecond photoconductive probes have been developed for use in pump and probe measurements [2]–[5]. In spite of their excellent bandwidths exceeding 200 GHz, pulse pattern injection over 10-Gb/s with >100-mV height has not been attained because of their low responsivities of less than 0.1 A/W and/or saturation limit. This letter reports on the first trial of our optoelectronic (OE) conversion stimulus probe head with a responsivity of 0.75 A/W and a bandwidth of 50 GHz.

II. Structure of OE Probe

Fig. 1 shows a schematic of the new optoelectronic active stimulus probe head. Optical beams coming from the FC/PC connector are introduced to a single mode fiber. A pair of optical lenses collimates and focuses the beams onto the side edge of the photo absorption layer of a 1.55-μm waveguide p–i–n photodiode (WGPD). This lens-based rigid assembly allows good reproducibility against overdriving stresses that arise when the probe tip is contacted to the device under measurement. The WGPD employs a novel multimode waveguide structure with doped InGaAsP intermediate-bandgap layers between the InGaAs core layer and the InP clad layers [6]. This permits waveguide multimode propagation resulting in a high external quantum efficiency of 60% or 0.75 A/W. The optical waveguide has a mushroom-mesa structure providing a 100 GHz bandwidth [6]. The WGPD output is introduced to a 50-Ω coplanar waveguide (CPW) on an alumina substrate. Along with the CPW, a dual bias network was formed by using discrete parts; a 400-pF blocking capacitor and two inductors, 4.5 nH each, (one for the WGPD and the other for the device to be excited by the probe). The lower cutoff frequency of the bias network is 40 MHz. The capacitor was made of a thin strip ferroelectric material (25-μm thick, 256-μm width, 1.8-mm long). The capacitor was put on the CPW center conductor and the center conductor was cut into two pieces at one side-edge of the capacitor. The center conductor cut apart from the capacitor was then contacted to the top electrode of the capacitor.

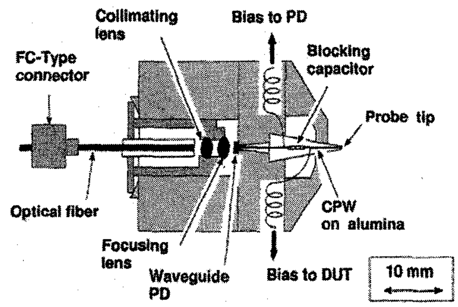

Fig. 1. Optoelectronic conversion stimulus probe head (bottom view). Inductors are assembled inside the metal block.

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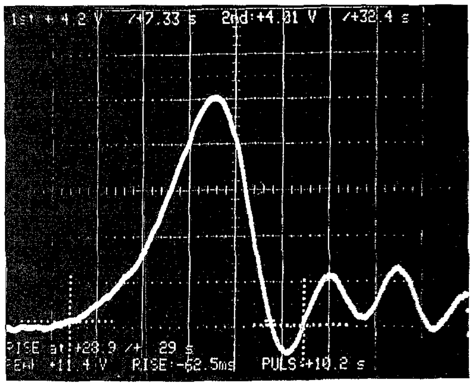
III. Experiments

Impulse response measurement was conducted by a pump and probe technique using electrooptic sampling (EOS). The probe tip was contacted to the near end of a 50-Ω CPW on a GaAs substrate with the far end terminated. The GaAs substrate was also utilized as an EO transducer. The electric field close to the contact pad of the OE probe was detected using the back illuminated direct sampling scheme [7].

An adiabatically compressed soliton pulse with 750-fs FWHM and 500-MHz repetition was used as the pump and probe pulse [8]. A typical measured output waveform is shown in Fig. 2. When incident average power attenuated to 20 μW, an average photo current of 15 μA was obtained, which implies a responsivity of 0.75 A/W. The output waveform shows asymmetrical response. The pulse width is 8.5 ps



(5 ps/div.)

Fig. 2. Impulse response of the optoelectronic stimulus prove head, measured by electrooptic sampling using a 750-fs FWHM symmetrical soliton pulse as a pump and probe signal.

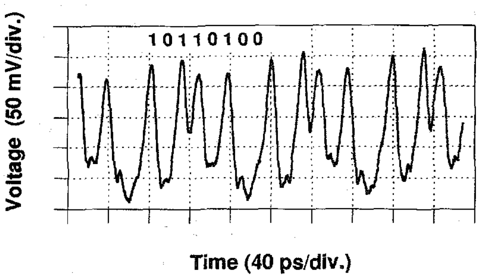


Fig. 3. Large-signal pulse pattern response of probe for 2mW, 64-Gb/s RZ repetitive optical pulse pattern, "10110100⋯" Output electrical pulse shows a peak height of 200 mV.

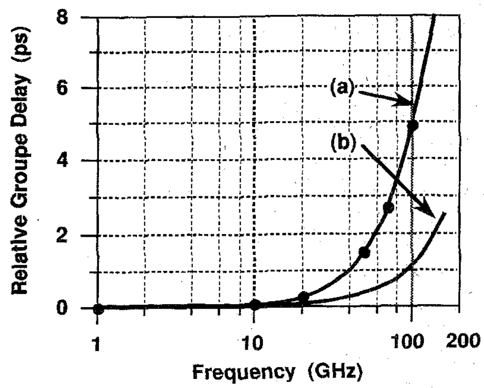


Fig. 4. Calculated dispersion characteristics; dots: results of electromagnetic simulator, solid lines: results of Hasnain's dispersion formulas. (a) the CPW used in the probe, (b) a half-sized CPW.

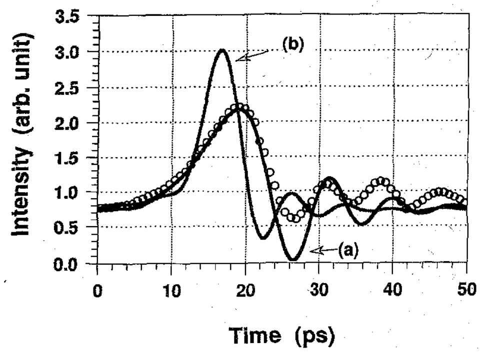


Fig. 5. Calculated impulse response of the probe. (a) response for the measured probe, and (b) response for a probe including half-sized CPW, open circles: measured result.

FWHM, and the rise and fall times within 10–90% are 10 ps and 4 ps, respectively. The effective 3-dB bandwidth was around 50 GHz. When used in the network measurement, detection bandwidth [4] of this probe can exceed 100 GHz. The peak voltage is estimated to be 150 mV. Output saturation voltage was 200 mVpp at the probe tip.

An optically generated 64-Gbs RZ pulse pattern [1] was injected into the OE probe. The pulse train has an 8-b repetitive pattern "10 110 100." The average power was 2 mW. The electrical output response was measured by EOS. A pulse-compressed, laser diode-pumped Nd:YLF laser generating 100 MHz, (1.1-ps FWHM pulses with very low jitter of <800 fs_{rms}) was used as the probe beam [7]. The measured waveform is shown in Fig. 3. Although the waveform degrades asymmetrically due to the dispersion of the CPW, 64-Gb/s RZ patterns can clearly be observed. The electrical pulse height was estimated to be 200 mV. This is the first demonstration of over 50-Gb/s and over 100-mVpp electrical pulse generation.

IV. Discussion

Fig. 4 shows the dispersion characteristics of the CPW calculated using the two-dimensional electromagnetic field simulator, "Em^{TM}." The CPW is comprised of a 6-μm-thick, 256-μm-width, 18-mm-long gold center conductor and 66-μm spaces. The substrate consists of 175-μm-thick alumina ($\varepsilon_r = 9.8$) with top covered 7-μm-thick polyimide ($\varepsilon_r = 4.0$). The result indicates that group delay monotonically increases to 5 ps at 100 GHz. This result agrees fairly well with the interpolation of measured S21 delay data (network analyzer measurement includes considerable residual phase error larger than 10 ps). The results also agree well with Hasnain's analytic dispersion formulas for CPW's [9], [10] where dispersion in this double dielectric layer structure can be approximated as a 175-μm-thick single dielectric structure with an ε_r of 8.56, which is shown by the solid line (a) in Fig. 4. Fig. 4 also shows the dispersion for a CPW whose dimensions (width/space/length) are scaled down by one half [solid line (b)]. It is clear that group delay can be markedly suppressed to 1.1 ps at 100 GHz.

Time domain responses for optoelectronic probes assuming the use of several types of transmission lines were analyzed using calculated group-delay data and measured S21 magnitude data of up to 110 GHz. The response of the WGPD itself was measured beforehand, and simply convolved. Fig. 5 shows the simulated impulse response for the probe: (a) the response for the measured probe, and (b) the response for a probe including the half-sized CPW. Simulated waveform (a) agrees well with the measured data. It is clear that asymmetrical waveform degradation is caused by the frequency dispersion of the CPW in the probe. To see more precisely, the measured waveform do not overlap the simulated waveform (a) after the peak. This would be due to radiative high-frequency attenuation [10] beyond the measured range of 110 GHz. In addition, the periodic tail oscillations are not centered around the baseline. This would be the result of small multiple-reflection superposed on the modal dispersion, because the WGPD output impedance ($\approx$100 Ω at 100 GHz) is not matched to the CPW impedance.

Waveform (b), however, suggests that the effect of dispersion can be sufficiently reduced (below 1 ps at 100 GHz) by scaling the CPW geometry (space/width/length) down to one half. It is noted that the radiative losses can also be reduced while ohmic losses are remained at the same level. If the alumina substrate is substituted with a lower dielectric material having an ε of $\sim$4, the dispersion is reduced to the same level in waveform (b) (the CPW geometry is subject to change so as to obtain the same characteristic impedance). Substitution of the CPW with a coax is another solution, which gives a dispersion-free performance up to the cutoff frequency of the coax. This will increase the bandwidth of the OE probe beyond 100 GHz because the WGPD itself already has a bandwidth this large.

V. Conclusion

We developed a highly efficient, broad-band optoelectronic stimulus probe employing a 1.55-μm waveguide p–i–n photodiode (WGPD). The novel multimode waveguide structure of the WGPD and optical lens-based rigid coupling assembly were responsible for yielding a very high responsivity of 0.75 A/W. The OE probe had an effective 3-dB bandwidth of 50 GHz which is currently limited by the frequency dispersion of the CPW used in the probe. 2-mW, 64-Gb/s RZ optical pulse patterns were successfully converted to 200 mVpp electrical signals. Reducing frequency dispersion is the key to enhancing the bandwidth of the probe to 100 GHz.

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