AFRL-SN-RS-TR-2004-281
Final Technical Report
October 2004

WIDEBAND ELECTROABSORPTION MODULATOR FOR MICROWAVE PHOTONICS

University of California, San Diego

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AFRL-SN-RS-TR-2004-281 has been reviewed and is approved for publication

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	OCTOBER 2004	Final Jun 02 – Jun 04

4. TITLE AND SUBTITLE
WIDEBAND ELECTROABSORPTION MODULATOR FOR MICROWAVE PHOTONICS

5. FUNDING NUMBERS
C - F30602-02-C-0155
PE - 62500F
PR - 2002
TA - SN
WU - 05

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8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/SNDP
25 Electronic Parkway
Rome New York 13441-4515

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
AFRL-SN-RS-TR-2004-281

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*
The technical objective/approach of this effort was to design and test a novel material and electrode structure of traveling wave electroabsorption modulators (TWEAMs) for use in microwave transmission systems exceeding frequencies of 50 GHz. Potential monolithic integration of these modulators with low noise lasers is promising for insertion into future space-based and air borne platforms in which physical size is a primary concern.

This report details the University of California at San Diego (UCSD) efforts in a collaborative research program with AFRL at Rome Research Site who evaluated the TWEAMS in fiber links. Significant progress has been made in the design and understanding of the electroabsorption modulator for analog fiber links. The present designs, including Intra-step-barrier Quantum Well (IQW) and Peripheral Coupled Waveguide (PCW), represent major advances in the transmitter development involving semiconductor external modulators. While low RF frequency modulators useful for analog links has been demonstrated, a follow-on program will be initiated to realize experimentally the analog performance of both regular traveling wave electrode and segmented-electrode traveling wave electroabsorption modulator in external modulated RF fiber-optic links.

14. SUBJECT TERMS
Optical Modulator, Analog Optical Links, Electroabsorption Modulator, RF Optical Links, Intra-step-Barrier Quantum Well, Peripheral Coupled Waveguides

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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1. Technical Objectives:

The main technical objective/approach was to design and test a novel material and electrode structure of traveling wave electroabsorption modulators (TWEAMs) for use in microwave transmission systems exceeding frequencies of 50 GHz. Potential monolithic integration of these modulators with low noise lasers is promising for insertion into future space-based and air borne platforms in which physical size is a primary concern.

This report details the University of California at San Diego (UCSD) efforts in a four year collaborative research program with AFRL at Rome Research Site who evaluated the TWEAMS in fiber links.

2. Overview:

The third year of the program produced the following accomplishments:

1. Demonstration of single-side band, frequency converted link using electroabsorption waveguide modulator and improve the link efficiency by more than 15 dB. The results have been published recently in a refereed journal [1].
2. Demonstration of a peripheral coupled waveguide concept for electroabsorption and electrorefraction waveguide waveguide devices. Similar design was first applied to the Franz-Keldysh effect modulator waveguide and has achieved a fiber-to-fiber optical insertion loss less than 8 dB.

The current year continued the above investigations with demonstration of an analog IQW EA modulator, and has:

1. incorporated the peripheral coupled optical waveguide in the MQW structure for TW-EAM for high multi-octave SFDR and high speed operation, and
2. designed advanced microwave electrode structure for the TW-EAM for impedance matching with the transmission line and loss microwave propagation loss.

3. Summary of accomplishments.

3.1. High saturation power IQW electroabsorption (EA) modulator

1. For the first time, multiple quantum well EA modulators have reached saturation powers up to ~100 mW.
2. High SFDRs are obtained with IQW EA modulator: two-tone multi-octave SFDR of 110 dB-Hz$^{2/3}$; single-octave SFDR of 121dB-Hz$^{4/5}$.

3.2. Near transparent link gain peripheral coupled waveguide EA modulator

1. For the first time, multiple quantum well EA modulators, incorporated with peripheral coupled waveguide (PCW), have demonstrated a RF link gain of –3 dB.
2. Very high SFDRs are obtained with PCW EA modulator: two-tone multi-octave SFDR of 118 dB-Hz$^{2/3}$; single-octave SFDR of 132 dB-Hz$^{4/5}$.

3.3. Design of segmented traveling wave EA modulator

1. For millimeter wave frequencies modulation, a simple yet comprehensive modeling approach is developed for analyzing the frequency response of segmented traveling-wave optical modulators.

4. Technical progress achieved on project.

4.1. High saturation power IQW electroabsorption (EA) modulator

The Intra-step-barrier Quantum Well (IQW) materials are grown by MOCVD. The InGaAsP/InGaAs IQW consists of 15 quantum wells and a 1.2 μm thick lower waveguiding layer designed for operation at 1550 nm wavelength. An optical propagation loss of 4 dB/mm is measured at 1568 nm. The details of the structure are reported in [2].

The measured RF link gain is improved by thickening the waveguide layer and by modifying the IQW layer thickness and number of quantum wells. Fig. 1 shows the results of the link gain measured up to 100 mW at 1 GHz for a 0.35 mm long device [2]. The detector responsivity is 0.7 A/W.

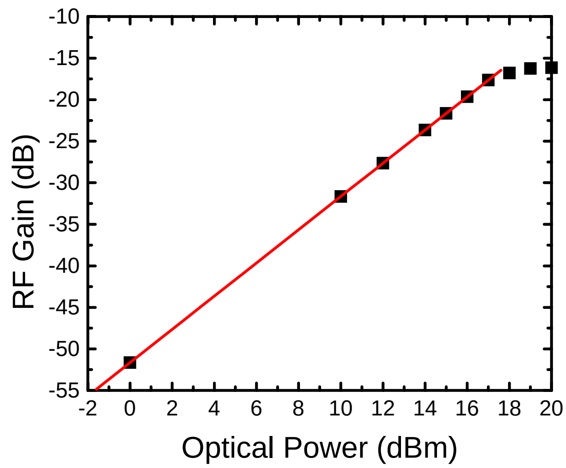


Fig. 1. Measured RF link gain versus optical power of an IQW-EAM that is 0.35 mm long, at 1543 nm wavelength.

A two-tone spurious free dynamic range (SFDR) measurement is done for this lumped electrode device at a frequency of ~600 MHz. The results are depicted in Fig. 2a. A multi-octave SFDR of 110 dB-Hz$^{2/3}$ and IIP3 ~ 15 dBm are observed at an input optical power of 15 dBm and at 1543 nm wavelength.

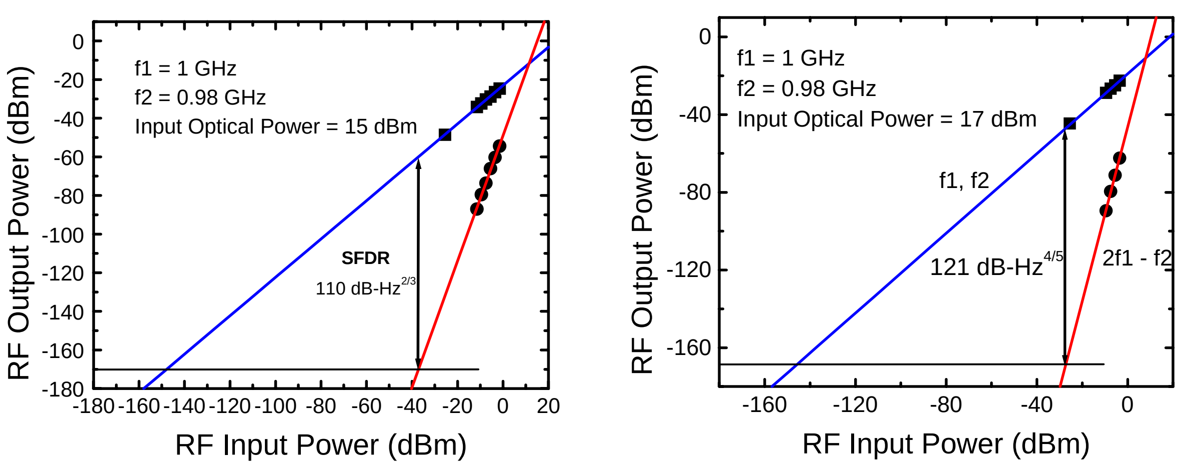


Fig. 2 (a). Two-tone multi-octave SFDR measurement for a 0.35 mm long device with lumped element electrode. The device is biased at the 2nd order null point, (b) single octave SFDR measurement at the 3rd order null point.

The single octave SFDR of the device was also evaluated. The optical input power to the EAM is 50 mW and the bias voltage is 3.3 V. The two RF tones are at 1 GHz and 0.98 GHz, respectively. From the insertion loss at bias point and the input optical power, it is estimate that the shot-noise-dominated noise floor is -168 dBm. The two-tone single-octave SFDR is 121dB-$Hz^{4/5}$, as shown in Fig. 2b.

4.2. Near transparent link gain peripheral couple waveguide EA modulator

The peripheral coupled waveguide (PCW) provides a means to decouple the microwave electrode design and the optical design in an EA modulator. The microwave electrode, including the EA region, is placed only peripheral to the optical waveguide mode, in its evanescent field. The small confinement factor in the EA layer reduces the photo-generated current per unit length, giving rise to high optical power handling in the EAM. The design of the microwave electrode will affect minimally the optical mode, so one can use very small EA layer thicknesses so as to obtain a small V_π. As the guided optical mode is located away from the surface, it encounters a small scattering loss. Thus the insertion loss can be reduced significantly. This allows one to increase the device length to ensure a low V_π. Furthermore, the optical waveguide will have a large mode size that matches to the single-mode fiber mode. The details of the design are reported in [3].

To demonstrate this concept, a PCW-EAM with a lumped-electrode is fabricated [3], in which the p-I(MQW)-n structure is grown on semi-insulating InP. The active region (0.1 μm thick) consists of five periods of InGaAsP wells and InGaAsP barriers. The exciton absorption peak of this MQW is set at 1480 nm. Underneath the active layers is a 1.7 μm thick InGaAsP (1.11 eV bandgap) lower cladding layer which leads to an optical waveguide structure like that of a one-sided large optical cavity where the majority of the

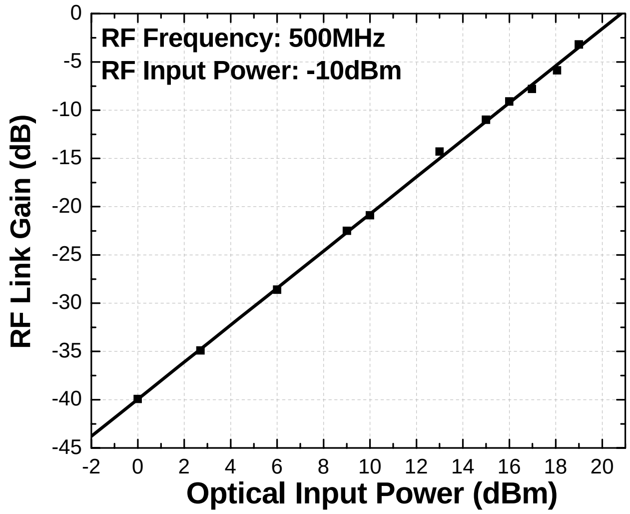
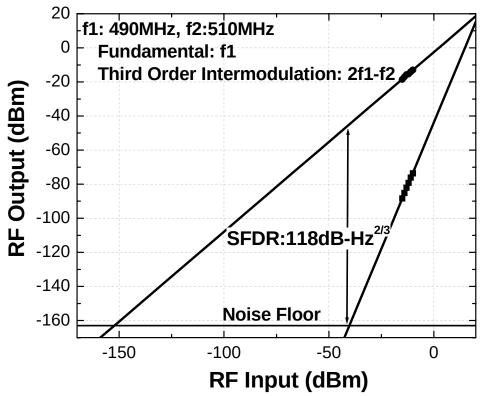
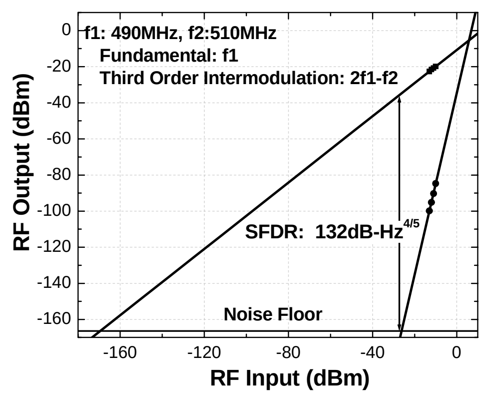


Fig. 3 RF link gain versus input optical power of the PCW-EAM

optical mode is confined in this lower cladding layer. The confinement factor of the EA layer is estimated at ~ 4%. The high optical saturation, low insertion loss and low V_π all work together in the same structure and yield an RF link gain of –3 dB (see Fig. 3) with large spurious-free dynamic range (>118 dB-Hz$^{2/3}$ for multi-octave SFDR and > 132 dB-Hz$^{4/5}$ single octave SFDR, as shown in Figs. 4a and 4b).



(a)



(b)

Fig. 4 (a) Measured fundamental and 3rd order intermodulation distortion signals at the second order null bias point, (b) measured fundamental and 3rd order intermodulation distortion (5th order nonlinearity dominated) at the 3rd order null bias point.

4.3. Design of segmented traveling wave EA modulator

The general requirements for traveling-wave electrodes are impedance matching, velocity matching, and low microwave loss. For traveling-wave EAMs, low-impedance matching is required, but velocity matching is not so important when the device is very short. However, with the consideration of PCW, a longer electrode (~1 mm) is required, there are certain advantages to use velocity matching traveling wave structures. It should be noted that the microwave velocities for transmission lines built on top of GaAs or InP are much faster than the optical group velocities in their optical waveguides, which is opposite to the case of traveling-wave $LiNbO_3$ modulators.

The segmented traveling-wave design, as illustrated in Fig. 5, employs a separate transmission line that runs parallel to the optical waveguide, with its microwave velocity faster than the optical group velocity, and its microwave impedance higher than 50 Ω (the impedance of the microwave source). The modulation length (and its capacitance) in the optical waveguide is segmented and periodically connected to the transmission line as capacitive loading, which lowers the microwave velocity and impedance. In the literature, this type of electrode is sometimes called "slow-wave transmission line" or "loaded line". The design goals are to match the lowered microwave velocity with the optical group velocity, and to match the lowered microwave impedance with 50 Ω.

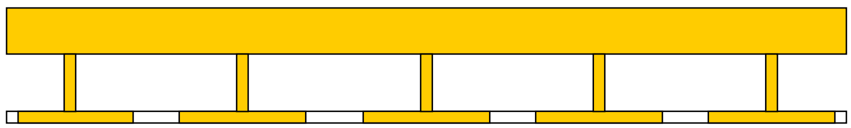


Fig. 5 Schematic diagram to show the traveling-wave electrode design. This can be a phase modulator, an electroabsorption modulator, or one arm of a Mach-Zehnder modulator.

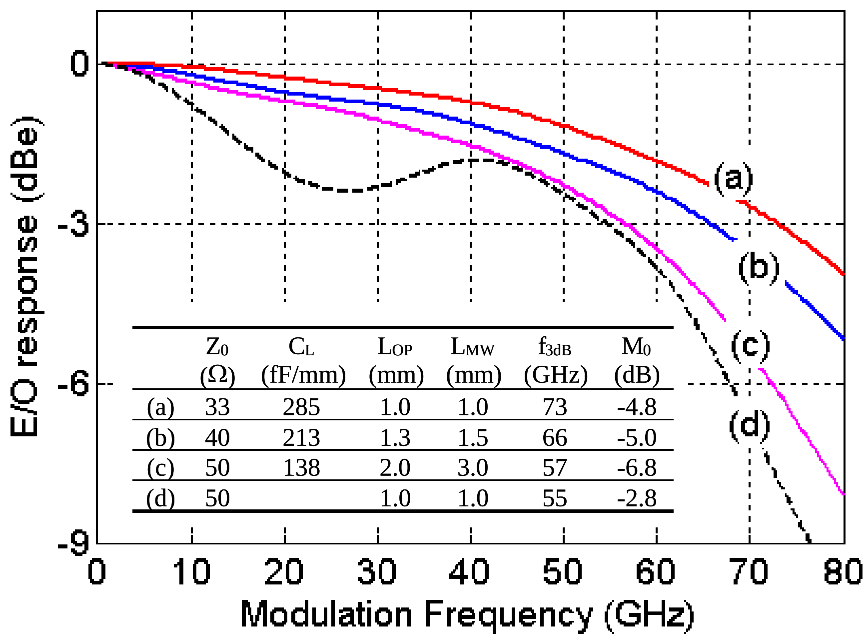
From a simple LC circuit model, the microwave impedance and the microwave velocity index for the unloaded and loaded transmission lines (assumed lossless) can be calculated [4], with L_μ and C_μ being the inductance and capacitance per unit-length for the unloaded transmission line, C_L the loaded capacitance per unit-length; Z_μ and n_μ are the microwave impedance and phase velocity index values before loading; Z_0 and n_0 are the corresponding parameter values after loading. The analysis obtains,

$$n_\mu Z_\mu = n_0 Z_0 \qquad (1)$$

$$C_L = \frac{n_0^2 - n_\mu^2}{c Z_0 n_0} \qquad (2)$$

The analysis shows that simultaneous impedance matching and velocity matching can be achieved if the unloaded transmission line and the capacitive loading are designed to satisfy the equations (1) and (2). For loading the same amount of total capacitance, larger C_L is desirable to keep the device shorter, which can reduce the optical loss and enhance the modulation bandwidth. From equation (2), when n_0 and Z_0 are fixed by the velocity matching and impedance matching requirements, n_μ should be as small as possible to improve C_L. This requires the unloaded transmission line to have a fast microwave velocity.

To account for the microwave loss, the microwave dispersion and filtering effects due to the periodic capacitive loading, and various parasitic effects, a microwave equivalent circuit model [4] for the segmented traveling-wave electrode, which consists of a total of N segments of active modulation waveguide periodically shunting with a transmission line, has been developed. The model has been tested for a $LiNbO_3$ modulator and excellent agreement has been obtained.



	Z_0 (Ω)	C_L (fF/mm)	L_{OP} (mm)	L_{MW} (mm)	f_{3dB} (GHz)	M_0 (dB)
(a)	33	285	1.0	1.0	73	-4.8
(b)	40	213	1.3	1.5	66	-5.0
(c)	50	138	2.0	3.0	57	-6.8
(d)	50		1.0	1.0	55	-2.8

Fig. 6. Calculated frequency responses for segmented traveling-wave EAMs using different terminator impedance Z0. The inset table shows the terminator impedance Z0, the capacitance loading capability CL (the unit is fF per mm of optical waveguide), the optical waveguide length LOP, the microstrip line length LMW, the resulted 3-dB bandwidth f3dB, and the relative E/O conversion gain M0 (at 0 Hz) compared with the 0.3 mm long lumped element design using 50 matching resistance.

With the segmented traveling-wave design for EA modulators, it is possible to improve the analog link performance. In exemplary designs, we assume the total active modulation length is 300 μm. It is divided into 6 segments and loaded to a microstrip transmission line. In the design, the inductance L_a is induced by the connection bridge; the resistance R_a includes the metal bridge resistance and the series resistance of the modulation waveguide; the capacitance C_a is the junction capacitance of the modulation waveguide. For each 50 μm long active segment, we take $C_a \sim 45$ fF, $R_a \sim 16\ \Omega$, and $L_a \sim 30$ pH. The frequency response curves calculated using our numerical modeling tool are presented in Fig. 6. The curves (a), (b) and (c) with loaded-line impedance matched to the terminator impedance of 33 Ω, 40 Ω and 50 Ω show bandwidths of 73 GHz, 66 GHz and 57 GHz, respectively. The efficiency compromise for the 3 designs is 4.8-6.8 dB, which is several dB better than the continuous TWEAM with similar bandwidth. The corresponding microwave reflections to the 50 Ω source from these segmented traveling-wave EAMs (STEAM) are shown in Fig. 7.

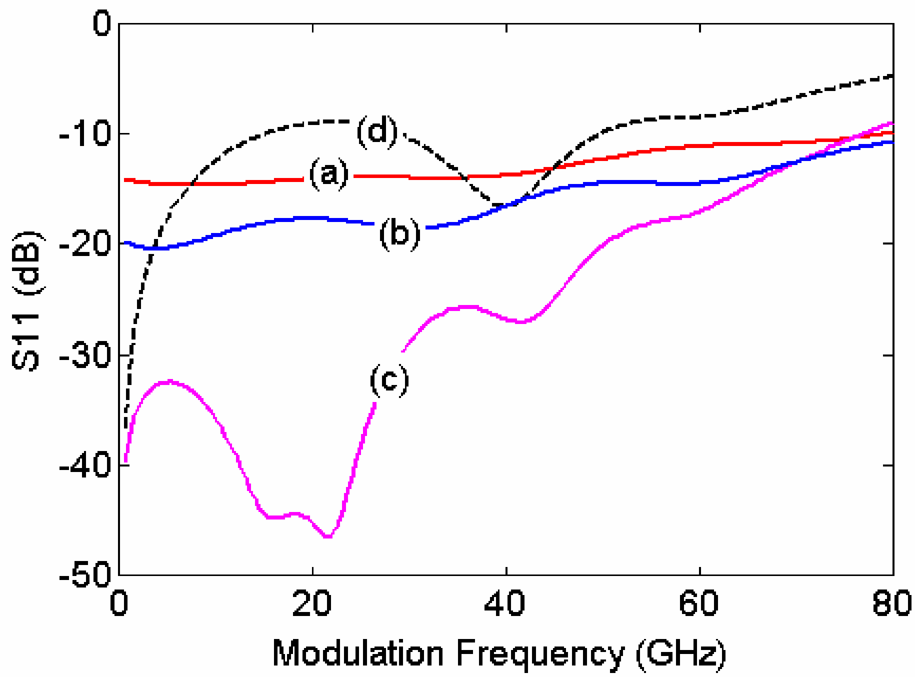


Fig. 7 Microwave return loss from the segmented traveling-wave EAMs to the 50 Ω source. The curve labels (a), (b), (c) and (d) correspond to the curve labels in Fig. 6.

5. Conclusion and future plan

Under the support of the Air Force Research Laboratory, significant progress has been made in the design and understanding of the electroabsorption modulator for analog fiber links. The present designs, including the IQW and the PCW waveguides, represent major advances in the transmitter development involving semiconductor external modulators.

While low RF frequency modulators useful for analog links has been demonstrated, a follow-on program will be initiated to realize experimentally the analog performance of both regular traveling wave electrode and segmented-electrode traveling wave electroabsorption modulator in external modulated RF fiber-optic links.

6. References.

1. Yang Wu, D.S. Shin, W.S.C. Chang, and P.K.L. Yu, "Microwave Photonics frequency-converted link using Electroabsorption devices," Journal of Semiconductor Technology and Science, Vol. 4, No. 1, p. 74-81, March 2004
2. J.X. Chen, Y. Wu, W. X. Chen,I. Shubin, A. Clawson, W. S. C. Chang, and P. K. L. Yu, "High-Power Intrastep Quantum Well Electroabsorption Modulator Using Single-sided Large Optical Cavity Waveguide", IEEE Photonics Technology Letters, Vol. 16, No. 2, p. 440-442, 2004
3. Y. Zhuang, W.S.Chang, and P.K.L. Yu, "Peripheral-Coupled-Waveguide MQW Electroabsorption Modulator for near transparency and high spurious free dynamic range RF fiber-optic Link, "IEEE Photonics Technology Letters, Vol. 16, No. 9, p. 2033-2035, 2004.
4. G.L. Li, T.G.B. Mason, P.K.L. Yu, "Analysis of Segmented Traveling-Wave Optical Modulator," IEEE/OSA Journal of Lightwave Technology, Vol 22, No. 7 p. 1789-1796 2004. (attachment 3).