

MICROCOPY RESOLUTION TEST CHART NATIONAL BUREAU OF STANDARDS-1963-A

.



CONTRACTOR DE LA CONTRACT

1. A. W

1.1

ARO 18054.10-EL

JUL 1 3 1284

099

12

07

ASYMMETRICAL COPLANAR TRANSMISSION LINES

TECHNICAL REPORT

T. KITAZAWA R. MITTRA

AD-A142 978

JUNE 1984

SUPPC TED BY U. S. ARMY F SEARCH OFFICE GRANT NO. D/ G29-82-K-0084

DTTC FILE COPY

ELECTROMAGNETICS LABORATORY DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING ENGINEERING EXPERIMENT STATION URBANA, ILLINOIS 61801

> APPROVED FOR PUBLIC RELEASE. DISTRIBUTION UNLIMITED.

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

REPORT DOCUMENTATION PAGE       REFORE CONCENTS FORM         1. REPORT NUMBER       1. GOV TOTALING FORM         4. TILE Fund Samma       1. GOV TOTALING FORM         A. TILE fund Samma       1. TYPE OF REPORT SCHOLETING FORM         ASTRMETRICAL COPLANAR TRANSMISSION LINES       1. TYPE OF REPORT & DEMONSTRUCTION TABLES         T. KITARTAKETANA       1. TYPE OF REPORT & DEMONSTRUCTION TABLES         T. KITARTAKETANA       1. TYPE OF REPORT & DEMONSTRUCTION TABLES         T. KITARTAKETANA       1. TYPE OF REPORT & DEMONSTRUCTION TABLES         T. KITARTAKETANA       1. CONTROLING OF GRANT AUWEER         D. BORTANIGO GRANTIANTION TABLE AND ADDRESS       1. CONTROLING OF GRANT AUWEER         D. BORTANICO GRANTIANTION TABLE AND ADDRESS       1. REPORT DATE         D. BORTANT RULES       1. REPORT DATE         D. BORTANT RULES       1. REPORT DATE         U. CONTROLING OFFICE ANA AD ADDRESS       1. REPORT DATE         U. SCHARTACTOR GRANT AUWEER       1. REPORT DATE         U. CONTROLING OFFICE ANA AD ADDRESS       1. REPORT DATE         U. CONTROLING OFFICE ANA AD ADDRESS       1. REPORT DATE         U. CONTROLING OFFICE ANA AD ADDRESS       1. REPORT DATE         U. CONTROLING OFFICE ANA AD ADDRESS       1. REPORT DATE         U. CONTROLING OFFICE ANA AD ADDRESS       1. REPORT DATE         U. O	SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)	
A PROAT NUMBER      I gov Log Blow as      Second Strates and	REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS
A TITLE (and Shaffid) ASYMMETRICAL COPLANAR TRANSMISSION LINES ASYMMETRICAL COPLANAR TRANSMISSION LINES A UTHORYS T. Kitazawa and R. Mittra A DEMONSMIC COMPACE AND ACOMPLIS Electromagnetics Laboratory Department of Electrical & Computer Engineering Diversity of Illinois, Urbana, Illinois 61801 P18054-EL 1. CONTROLUME OFFICE AND ACOMPLIS Line 1984 1. CONTROLUME OFFICE AND ACOMPLIS LINE FORTOACH Research Triangle Park, N.C. 27709 1. SECURITY CLASS (of the report) UNCLASSIFIED 1. SECURITY CLASS (of the report) DISTRIBUTION STATEMENT (of the Astrony Internet in Biock 10, if different inter Report) 2. OSTABLY ON STATEMENT (of the Astrony of Identify by Side Annow?) AND TORMS on this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 3. KY ONDS (Commune and the incessary and Identify by Side Annow?) AND TATEMENT (Continue and repressions of the line Capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the line apacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	1. REPORT NUMBER 2. GOVT ACCESSION &	RECIPIENT'S CATALOG NUMBER
TITLE (and Submitu)     SYMMETRICAL COPLANAR TRANSMISSION LINES     ASYMMETRICAL COPLANAR TRANSMISSION LINES     THE OF REPORT & PERSON COVERED     SECURPTION OF A CONTRACT OF READY NUMBER     ASYMMETRICAL COPLANAR TRANSMISSION LINES     THE CONTRACT OF REPORT NUMBER     ASYMMETRICAL COPLANAR TRANSMISSION LINES     THE CONTRACT OF REPORT NUMBER     ASYMMETRICAL COPLANAR TRANSMISSION LINES     THE CONTRACT OF REPORT NUMBER     ASYMMETRICAL COPLANAR TRANSMISSION LINES     THE CONTRACT OF READY NUMBER     ASYMMETRICAL COPLANAR TRANSMISSION LINES     ASYMETRICAL COPLANAR TRANSMISSION     ASYMETRICAL COPLANAR TRANSMISSION LINES     ASYMETRICAL COPLANAR TRANSMISSI	ANAT	X
ASYMMETRICAL COPLANAR TRANSMISSION LINES	4. TITLE (and Subtitie)	S. TYPE OF REPORT & PERIOD COVERED
AUTHOR(0)     T. Kitazawa and R. Mittra     DAG-29-82-K-0084     CONTROLOGICAL SECTION NAME AND ADDRESS     Electromagnetics Laboratory     Department of Electrical & Computer Engineering     University of Ellinois, Urbana, Illinois 61801     PIB054-EL     University of Ellinois, Urbana, Illinois 61801     University of Fraces     U. S. Army Research Office     June 1984     UNIVERSITY CLASS. (of this report)     UNCLASSIFIED     UNIVERSITY CLASS. (of this report)     UNCLASSIFIED     UNIVERSITY CLASS. (of this report)     UNCLASSIFIED     University of public release.     CONTRIBUTION STATEMENT (of the abstract entered in Block 10, 11 different the Report)     UNCLASSIFIED     SCHEDULE     Approved for public release.     CONTRIBUTION STATEMENT (of the abstract entered in Block 10, 11 different the Report)     UNCLASSIFIED     SCHEDULE     Actional expressions of the State matery     Actional expressions of the State matery     Material Conductions on reverse stat. Increasery of Adventive by Mach number)     integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates     Aggrade/(Continue on reverse stat. Increasery of Adventive by State matery     Material Conduction of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	ASYMMETRICAL COPLANAR TRANSMISSION LINES	Technical Report
AUTHOR(s)		
7. AUTHON(1)       1. CONTRACT OF GRANT NUMBER(1)         7. Kitzzawa and R. Mittra       1. CONTRACT OF GRANT NUMBER(1)         8. FERFORMING ORGANIZATION NAME AND ADDRESS       10. PROGRAM ELSUET, PROJECT, TASK         Electromagnetics Laboratory       10. PROGRAM ELSUET, PROJECT, TASK         Department of Electrical & Computer Engineering       10. PROGRAM ELSUET, PROJECT, TASK         University of Illinois, Urbana, Illinois 61801       P18054-EL         10. CONTROLLING OFFICE NAME AND ADDRESS       12. REPORT DATE         11. CONTROLLING OFFICE NAME AND ADDRESS       13. NUMBER OF FACES         12. S. Army Research Office       June 1984         P. O. Box 12211       13. NUMBER OF FACES         Research Triangle Park, N.C. 27709       13. SUBME CLASS (of inte report)         UNCLASSIFIED       13. SUBME CLASS (of inte report)         Distribution Unlimited.       Approved for public release.         77. DISTRIBUTION STATEMENT (of the Abstract entered in Block 10, 11 different frem Report)         Distribution Statement (of the Army position, unless so designated by other authorized documents.         B. ACT ORGANIZATION and Provide and the asymmetric geometry, isotropic and anisotropic substrates         C. ASTRIBUTION STATEMENT (of the asymmetrical coplanar strip line are derived for the interestions of the line Capacitances of the asymmetrical coplanar strip line are derived for the interestion strip line are derived for the capacitance and is shown	,	15. PERFORMING ORG. REPORT NUMBER
<ul> <li>Kitzazawa and R. Mittra</li> <li>DAGG-29-82-K-0084</li> <li>PROGRAM CLEMENT AND ADDRESS</li> <li>Electromagnetics Laboratory</li> <li>Department of Electrical &amp; Computer Engineering</li> <li>UNIVERSITY of Illinois, Urbana, Illinois 61801</li> <li>PROGRAM CLEMENT AND ADDRESS</li> <li>S. Army Research Office</li> <li>P. 0. Box 12211</li> <li>Research Triangle Park, N.C. 27709</li> <li>S. SECURITY CLASS (of the report)</li> <li>UNCLASSIFIED</li> <li>Is SECURITY CLASS (of the report)</li> <li>UNCLASSIFIED</li> <li>Is SECURITY CLASS (of the report)</li> <li>DISTRIBUTION STATEMENT (of the abstract entered in Block 10, 11 different Imm Report)</li> <li>DISTRIBUTION STATEMENT (of the abstract entered in Block 10, 11 different Imm Report)</li> <li>Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>AREY WORDS (Commune on review and (Incessent of the Incessent of the Incessent of the apprentiation of the apprentiating apprentiation of the</li></ul>	7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(1)
PERFORMING ORGANIZATION NAME AND ADDRESS     Electromagnetics Laboratory     Department of Electrical & Computer Engineering     University of Illinois, Urbana, Illinois 61801     I. CONTROLLING OFFICE NAME AND ADDRESS     I. REPORT OATE     June 1984     I. A REPORT OATE     June 1984     I. A REPORT OATE     JUNE 1984     I. NUMBER OF PACES     Z8     Second Triangle Park, N.C. 27709     I. NUMBER OF PACE     Z8     Second Triangle Park, N.C. 27709     I. Second Triangle Park, N.C. 27709     June 1984     I. NUMBER OF PACES     Z8     Second Triangle Park, N.C. 27709     I. NUMBER OF PACE     Z8     Second Triangle Park, N.C. 27709     June 1984     June 1984     I. NUMBER OF PACES     Z8     Second Triangle Park, N.C. 27709     June 1984     I. NUMBER OF PACES     Z8     Second Triangle Park, N.C. 27709     June 1984     June 1984     June 1984     June 1984     I. NUMBER OF PACES     Z8     Second Triangle Park, N.C. 27709     June 1984     June 198     June	T. Kitazawa and R. Mittra	DAAG-29-82-K-0084
<ul> <li>PERFORMING ORGANIZATION NAME AND ACORESS Electromagnetics Laboratory Department of Electrical &amp; Computer Engineering University of Illinois, Urbana, Illinois 61801 II. CONTROLLING OFFICE NAME AND ACORESS U. S. Army Research Office JU. S. Army Research Office JU. S. Army Research Office II. CONTROLLING OFFICE NAME AND ACORESS U. S. Army Research Office II. CONTROLLING OFFICE NAME AND ACORESS II. S. Army Research Office II. CONTROLLING OFFICE NAME AND ACORESS II. S. Army Research Office II. CONTROLLING OFFICE NAME AND ACORESS II. S. Army Research Office II. CONTROLLING OFFICE NAME AND ACORESS(II different free Controlling Office) II. CONTROLLING OFFICE NAME AND ACORESS(II different free Controlling Office) II. S. SCHEDVICE II. S. CONTROLLING OFFICE NAME AND ACORESS(II different free Controlling Office) II. S. DEFINITY CLASS (of the report) UNCLASSIFIED II. DESTRIBUTION STATEMENT (of the Acore intered in Black 20, If different free Report) II. DISTRIBUTION STATEMENT (of the Acore intered in Black 20, If different free Report) II. DISTRIBUTION STATEMENT (of the Acore intered in Black 20, If different free Report) II. DISTRIBUTION STATEMENT (of the Acore intered in Black 20, If different free Report) II. DISTRIBUTION STATEMENT (of the Acore intered in Black 20, If different free Report) II. S. Army Proved for public release. II. DISTRIBUTION STATEMENT (of the Acore intered in Black 20, If different free Report) II. S. XEY WACD (Continue on reviews side if necessary and identify by black number) II. S. AND ACCORDING ON CONTRACT, Confirme on control of the line capacitances of the asymmetrical COPLIANT AVERAGE A. AND ACCORDING ON CONTRACT, Confirme on control of the line capacitances of the asymmetrical COPLIANT AVERGENT (of the Acore and its shown to yield accurate results for both isotropic and anisotropic substrates. </li> </ul>		
<ul> <li>Reforming on anization name and address</li> <li>Reforming on anization name and address</li> <li>Reforming on anization name and address</li> <li>Reforming the suboratory</li> <li>Department of Electrical &amp; Computer Engineering</li> <li>University of Illinois, Urbana, Illinois 61801</li> <li>P18054-EL</li> <li>Controlling office NAME and Address</li> <li>S. Army Research Office</li> <li>S. Army Researc</li></ul>		
Department of Electrical & Computer Engineering University of Illinois, Urbana, Illinois 61801 12. REPORT DATE U. S. ATTY Research Office P. O. Box 12211 Research Triangle Park, N.C. 27709 13. NUMBER OF PAGES Research Triangle Park, N.C. 27709 14. WONITOWING AGENCY NAME & ADDRESS(I different free Convolting Office) 15. SECURITY CLASS.(of this report) UNCLASSIFIED 14. DISTRIBUTION STATEMENT (of this Report) Distribution Unlimited. Approved for public release. 17. DISTRIBUTION STATEMENT (of this Report) Distribution STATEMENT (of this Report) Distribution STATEMENT (of this Report) 15. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 1. XEY WORDS (Combines on reviews side if necessary and identify by block number) Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 1. AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and identify by block number) AMSTRACT (Combines on reviews side if necessary and	FERFORMING ONGANIZATION NAME AND ADDRESS Electromagnetics Laboratory	AREA & WORK UNIT NUMBERS
University of Illinois, Urbana, Illinois 61801 P18054-EL P18054-	Department of Electrical & Computer Engineering	
<ul> <li>12. CONTROLLING OFFICE NAME AND ADDRESS</li> <li>12. REPORT DATE</li> <li>13. NUMBER OF PAGES</li> <li>14. NUMBER OF PAGES</li> <li>15. SECURITY CLASS. (of this report)</li> <li>16. DISTRIBUTION STATEMENT (of this Report)</li> <li>Distribution Unlimited.</li> <li>Approved for public release.</li> <li>17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, 11 different from Report)</li> <li>16. SUPPLEMENTARY HOTES</li> <li>17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, 11 different from Report)</li> <li>17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, 11 different from Report)</li> <li>18. SUPPLEMENTARY HOTES</li> <li>19. KEY WORDS (Continue on reverse side if necessary and identify by block number)</li> <li>11. Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>14. Additional expressions of the line capacitances of the asymmetrical coplanar strip line are derived for the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li> </ul>	University of Illinois, Urbana, Illinois 61801	P18054-EL
U. S. Army Research Office P. O. Box 12211 Research Triangle Park, N.C. 27709 14. WONITORING AGENCY NAME & ACORESS(II different from Controlling Office) 14. WONITORING AGENCY NAME & ACORESS(II different from Controlling Office) 15. SECURITY CLASS. (of this report) UNCLASSIFIED 15. DECLASSIFICATION DOWNGRACING 16. DISTRIBUTION STATEMENT (of this Report) Distribution Unlimited. Approved for public release. 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, II different from Report) 18. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 3. XEY WORDS (Continue on reverse side II necessary and Identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 4. AgeTRACT (Command expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE
<ul> <li>P. O. Box 12211 Research Triangle Park, N.C. 27709 13. MONITORING AGENCY NAME &amp; ADDRESS(// different from Controlling Office) 14. MONITORING AGENCY NAME &amp; ADDRESS(// different from Controlling Office) 15. SECURITY CLASS. (of this report) UNCLASSIFIED 13. DECLASSIFICATION DOWNGRACING 3. OISTRIBUTION STATEMENT (of the Report) Distribution Unlimited. Approved for public release. 17. DISTRIBUTION STATEMENT (of the observer entered in Block 20, 1/ different from Report) 18. SUPPLEMENTARY MOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 3. KEY WORDS (Continue on reverse side if necessary and identify by block number) Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 3. AgeTRACT (Continue on reverse side if necessary and identify by block number) Control of the Army position of the line capacitances of the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li></ul>	U. S. Army Research Office	June 1984
Kessearcn Triangle Park, N.C. 27709       28         14. WONITORING AGENCY NAME & ADDRESS(II dillorent from Controlling Office)       15. SECURITY CLASS. (of this report)         13. SECURITY CLASS. (of this report)       13. SECURITY CLASS. (of this report)         13. DECLASSIFICATION DOWNGRACING       13. SECURITY CLASS. (of this report)         13. DECLASSIFICATION DOWNGRACING       13. SECURITY CLASS. (of this report)         13. DECLASSIFICATION DOWNGRACING       13. SECURITY CLASS. (of this report)         14. OISTRIBUTION STATEMENT (of the Abstract entered in Block 20, if different from Report)       13. SECURITY NOTES         7. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)       14. Security NOTES         7. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)       14. Security NOTES         7. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)       15. Security NOTES         7. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)       15. Security NOTES         8. SUPPLEMENTARY NOTES       15. Security NOTES       15. Security NOTES         9. KEY WORDS (Comme on reverse side if necessary and identify by block number)       16. Security NoteS (Comme on reverse side if necessary and identify by block number)         11. Security of the abstract side if necessary and identify by block number)       16. Security block number)         7. V	P. 0. Box 12211	13. NUMBER OF PAGES
In account of the second and another and the second and the second account of the se	Research Triangle Park, N.C. 27709	
13. DECLASSIFIED 13. DECLASSIFICATION DOWNGRACING SCHEDULE 13. DECLASSIFICATION DOWNGRACING SCHEDULE 13. DECLASSIFICATION DOWNGRACING SCHEDULE 13. DECLASSIFICATION DOWNGRACING SCHEDULE 13. DECLASSIFICATION DOWNGRACING SCHEDULE 13. DECLASSIFICATION DOWNGRACING SCHEDULE 13. DECLASSIFICATION DOWNGRACING 15. DECLASSIFICATION DOWN		
15. DECLASSIFICATION DOWNGRACING SCHEOULE 16. OISTRIBUTION STATEMENT (of this Report) Distribution Unlimited. Approved for public release. 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) 18. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 8. KEY WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 8. AgeTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.		OUCTOOTLIED
<b>18.</b> DISTRIBUTION STATEMENT (of the Report) Distribution Unlimited. Approved for public release. <b>17.</b> DISTRIBUTION STATEMENT (of the abstract intered in Block 20, if different from Report) <b>18.</b> SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. <b>3.</b> KEY WORDS (Continue on reverse side if necessary and identify by block number) Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates <b>4.</b> Apprecent of the any metrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.		154. DECLASSIFICATION DOWNGRACING
<ul> <li>Approved for public release.</li> <li>Distribution Unlimited.</li> <li>Approved for public release.</li> <li>Distribution STATEMENT (of the abstract entered in Block 20, if different from Report)</li> <li>SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number)</li> <li>Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>AMSTRACT (Continue on reverse side if necessary and identify by block number)</li> <li>Contract of the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li> </ul>		
Distribution Unlimited. Approved for public release. 7. DISTRIBUTION STATEMENT (of the observed million 20, 11 different from Report) 4. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 9. KEY WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 9. AMSTRACT (Continue on reverse side if necessary and identify by block number) Coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	a. UISTRIBUTION STATEMENT (of this Report)	
Approved for public release. 7. DISTRIBUTION STATEMENT (of the observed in Block 20, if different from Report) 8. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 9. KEY WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 9. AMSTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	Distribution Unlimited.	
<ul> <li>Approved for public release.</li> <li>I. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)</li> <li>I. Department of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.</li> <li>XEY WORDS (Continue on reverse side if necessary and identify by block number)</li> <li>Integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>AgeTMACT (Continue on reverse side if necessary and identify by block number)</li> <li>Yariational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li> </ul>	Approved for public release	
<ul> <li>17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)</li> <li>18. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.</li> <li>2. KEY WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>3. Aggreact; (Continue on reverse side if necessary and identify by block number) <ul> <li>Yes a state of the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li> </ul></li></ul>	Approved for public release.	
<ul> <li>IN DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)</li> <li>SUPPLEMENTARY NOTES         The findings in this report are not to be construed as an official             Department of the Army position, unless so designated by other authorized             documents.         Integrated circuits; coplanar lines; assymetric geometry, isotropic and             anisotropic substrates         Asstract: (Continue on reverse side if necessary and identify by block number)         The first time. An efficient numerical method is employed to compute the line             capacitance and is shown to yield accurate results for both isotropic and             anisotropic substrates.</li></ul>		
<ul> <li>SUPPLEMENTARY NOTES         The findings in this report are not to be construed as an official             Department of the Army position, unless so designated by other authorized             documents.         Integrated circuits; coplanar lines; assymetric geometry, isotropic and             anisotropic substrates         Asstract (Continue on reverse side 11 necessary and identify by block number)          The final expressions of the line capacitances of the asymmetrical             coplanar waveguide and the asymmetrical coplanar strip line are derived for the             first time. An efficient numerical method is employed to compute the line             capacitance and is shown to yield accurate results for both isotropic and             anisotropic substrates.</li></ul>		(rom Report)
<ul> <li>SUPPLEMENTARY NOTES         The findings in this report are not to be construed as an official             Department of the Army position, unless so designated by other authorized             documents.         XEV WORDS (Continue on reverse side (I necessary and identify by block number)             integrated circuits; coplanar lines; assymetric geometry, isotropic and             anisotropic substrates         ABSTRACT (Continue on reverse side (I necessary and identify by block number)             Yariational expressions of the line capacitances of the asymmetrical             coplanar waveguide and the asymmetrical coplanar strip line are derived for the             first time. An efficient numerical method is employed to compute the line             capacitance and is shown to yield accurate results for both isotropic and             anisotropic substrates.</li></ul>	7. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different a	
<ul> <li>SUPPLEMENTARY NOTES         The findings in this report are not to be construed as an official             Department of the Army position, unless so designated by other authorized             documents.         XEY WORDS (Continue on reverse side if necessary and identify by block number)             integrated circuits; coplanar lines; assymetric geometry, isotropic and             anisotropic substrates         Asstract; (Continue on reverse side if necessary and identify by block number)             Yariational expressions of the line capacitances of the asymmetrical             coplanar waveguide and the asymmetrical coplanar strip line are derived for the             first time. An efficient numerical method is employed to compute the line             capacitance and is shown to yield accurate results for both isotropic and             anisotropic substrates.</li></ul>	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different i	
<ul> <li>SUPPLEMENTARY NOTES         The findings in this report are not to be construed as an official             Department of the Army position, unless so designated by other authorized             documents.         XEY WORDS (Continue on reverse side if necessary and identify by block number)             integrated circuits; coplanar lines; assymetric geometry, isotropic and             anisotropic substrates         ASSTRACT (Continue on reverse side if necessary and identify by block number)             Yariational expressions of the line capacitances of the asymmetrical             coplanar waveguide and the asymmetrical coplanar strip line are derived for the             first time. An efficient numerical method is employed to compute the line             capacitance and is shown to yield accurate results for both isotropic and             anisotropic substrates.</li></ul>	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different i	
The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents. 3. KEY WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates 4. AMSTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different .	
<ul> <li>MEY WORDS (Continue on reverse side if necessary and identify by block number)     integrated circuits; coplanar lines; assymetric geometry, isotropic and     anisotropic substrates</li> <li>AMSTRACT (Continue on reverse side if necessary and identify by block number)</li></ul>	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different .	
<ul> <li>XEY WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>AMSTRACT (Continue on reverse side if necessary and identify by block number)</li></ul>	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different 18. SUPPLEMENTARY NOTES The findings in this report are not to be constru Department of the American states and the states and the states and the states are not to be constru-	ed as an official
<ul> <li>XEV WORDS (Continue on reverse side if necessary and identify by block number) integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates</li> <li>AESTRACT (Continue on reverse side if necessary and identify by block number)         Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li> </ul>	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different 18. SUPPLEMENTARY NOTES The findings in this report are not to be constru Department of the Army position, unless so design documents.	ed as an official lated by other authorized
integrated circuits; coplanar lines; assymetric geometry, isotropic and anisotropic substrates <sup>0.</sup> ABSTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different 18. SUPPLEMENTARY NOTES The findings in this report are not to be constru Department of the Army position, unless so design documents.	ed as an official ated by other authorized
<ul> <li>AMSTRACT (Continue on reverse side II necessary and identify by block number)</li> <li>AMSTRACT (Continue on reverse side II necessary and identify by block number)</li> <li>Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.</li> </ul>	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different 18. SUPPLEMENTARY NOTES The findings in this report are not to be constru Department of the Army position, unless so design documents. 19. KEY WORDS (Continue on reverse side if necessary and identify by block number	ed as an official wated by other authorized
O ANSTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different 18. SUPPLEMENTARY NOTES The findings in this report are not to be constru Department of the Army position, unless so design documents. 19. KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits: conlanar lings: assumpting of	ed as an official lated by other authorized
<sup>0.</sup> AGSTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	<ul> <li>DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru Department of the Army position, unless so design documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> </ul>	ed as an official ated by other authorized " eometry, isotropic and
<sup>0.</sup> ABSTRACT (Continue on reverse side if necessary and identify by block number) Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	<ul> <li>17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>18. SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru</li> <li>Department of the Army position, unless so design documents.</li> <li>3. KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> </ul>	ed as an official hated by other authorized w) seometry, isotropic and
~ Variational expressions of the line capacitances of the asymmetrical coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	<ul> <li>17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>18. SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru</li> <li>Department of the Army position, unless so design documents.</li> <li>9. KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> </ul>	ed as an official ated by other authorized "" eometry, isotropic and
coplanar waveguide and the asymmetrical coplanar strip line are derived for the first time. An efficient numerical method is employed to compute the line capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	<ol> <li>DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru Department of the Army position, unless so design documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>ABSIRACT (Continue on reverse side if necessary and identify by block number</li> </ol>	ed as an official hated by other authorized w) eometry, isotropic and
capacitance and is shown to yield accurate results for both isotropic and anisotropic substrates.	<ul> <li>DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru Department of the Army position, unless so design documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>AMSTRACT (Continue on reverse side if necessary and identify by block number Variational expressions of the line capacita</li> </ul>	ed as an official hated by other authorized m ecometry, isotropic and r nces of the asymmetrical
anisotropic substrates.	<ul> <li>DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru Department of the Army position, unless so design documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>ABSTRACT (Continue on reverse side if necessary and identify by block number Variational expressions of the line capacita coplanar waveguide and the asymmetrical coplanar</li> </ul>	ed as an official hated by other authorized "" ecometry, isotropic and " nces of the asymmetrical strip line are derived for the
	<ul> <li>17. DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>18. SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru</li> <li>Department of the Army position, unless so design documents.</li> <li>19. KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>0. ABSTRACT (Continue on reverse side if necessary and identify by block number of Variational expressions of the line capacita coplanar waveguide and the asymmetrical coplanar first time. An efficient numerical method is employed and the number of the symmetrical method is employed and the asymmetrical method is employed and the method is employed and</li></ul>	ed as an official hated by other authorized "" ceometry, isotropic and "" nces of the asymmetrical strip line are derived for the loyed to compute the line
	<ul> <li>DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different is supplementary notes</li> <li>The findings in this report are not to be construined to be construined in the Army position, unless so design documents.</li> <li>XEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>AMSTRACT (Continue on reverse side if necessary and identify by block number of variational expressions of the line capacita coplanar waveguide and the asymmetrical coplanar first time. An efficient numerical method is emp capacitance and is shown to yield accurate result anisotropic substrates</li> </ul>	ed as an official hated by other authorized w ecometry, isotropic and r, nces of the asymmetrical strip line are derived for the loyed to compute the line s for both isotropic and
	<ul> <li>DISTRIBUTION STATEMENT (of the abetract entered in Block 20, if different</li> <li>SUPPLEMENTARY NOTES</li> <li>The findings in this report are not to be constru</li> <li>Department of the Army position, unless so design documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>AESTRACT (Continue on reverse side if necessary and identify by block number 'Variational expressions of the line capacita coplanar waveguide and the asymmetrical coplanar first time. An efficient numerical method is emp capacitance and is shown to yield accurate result anisotropic substrates.</li> </ul>	ed as an official hated by other authorized w eometry, isotropic and r nces of the asymmetrical strip line are derived for the loyed to compute the line s for both isotropic and
	<ul> <li>DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different in Statement of the second provided in Block 20, if different in the findings in this report are not to be construe Department of the Army position, unless so design documents.</li> <li>KEY WORDS (Continue on reverse side if necessary and identify by block number integrated circuits; coplanar lines; assymetric g anisotropic substrates</li> <li>ABSTRACT (Continue on reverse side if necessary and identify by block number of the line capacita coplanar waveguide and the asymmetrical coplanar first time. An efficient numerical method is emp capacitance and is shown to yield accurate result anisotropic substrates.</li> </ul>	ned as an official hated by other authorized "" neometry, isotropic and "" nces of the asymmetrical strip line are derived for the loyed to compute the line s for both isotropic and

2.2.2

SECURITY CLASSIFICATION OF THIS PAGE (When Deta Entered)

UILU-84-2546

Electromagnetics Laboratory Report No. 84-9

ASYMMETRICAL COPLANAR TRANSMISSION LINES

by

T. Kitazawa R. Mittra

Electromagnetics Laboratory Department of Electrical and Computer Engineering University of Illinois at Urbana-Champaign Urbana, Illinois 61801

Technical Report



June 1984

Supported by

U. S. Army Research Office Contract No. DAAG29-82-K-0084

# TABLE OF CONTENTS

ACCESS TOTAL

		Page			
I.	INTRODUCTION	. 1			
11.	THEORY	. 2			
	<ul> <li>A. Variational Expression for the Line Capacitance of ACPW</li> <li>B. Variational Expression for the Line Capacitance of ACSL</li> <li>C. Method of Solution</li></ul>	. 2 . 5 . 7			
111.	NUMERICAL RESULTS	. 9			
IV.	CONCLUSIONS	. 17			
	APPENDIX I: ASYMMETRICAL COPLANAR WAVEGUIDE AND ASYMMETRICAL COPLANAR STRIP LINE WITHOUT SUBSTRATE				
	REFERENCES	. 24			

# LIST OF FIGURES

0.00

KARKAN NEWYAN

**COUNT** 

and the set

aceses ' France and

Figure		Page
1.	Asymmetrical coplanar transmission lines	3
2.	ACPW on isotropic dielectric substrate	12
3.	ACPW on anisotropic sapphire substrate	13
4.	ACSL on isotropic dielectric substrate	14
5.	ACSL on anisotropic boron-nitride substrate	15
6.	A series of transformations for the asymmetrical coplanar waveguide without substrates	19-20
7.	A series of transformations for the asymmetrical coplanar strip line without substrate	21-22

a na indra indra indra i

# LIST OF TABLES

Table		Page
1.	Line capacitance of ACPW C/ $\varepsilon_0$	10
2.	Line capacitance of ACSL C/ $\varepsilon_0$	11

#### I. INTRODUCTION

Coplanar transmission-line structures have received considerable attention due to their easy adaptation to shunt elements. The characteristics of symmetrical coplanar transmission lines have been investigated by many authors for both isotropic and anisotropic substrates [1], [2], [3], [4], [5]. Recently, asymmetrical versions of these coplanar lines have been introduced [6], [7], because of additional flexibilities offered by the asymmetric configuration in the design of microwave integrated circuits (MIC).

and the second sec

This paper derives two variational expressions for the line capacitances of the asymmetrical coplanar waveguide (ACPW) and the asymmetrical coplanar strip line (ACSL) that are general enough to be applicable to either the isotropic or uniaxially anisotropic substrates. These expressions are then employed in conjunction with an accurate and efficient numerical method which computes the line characteristics, viz., the effective dielectric constant and the characteristic impedance of ACPW and ACSL with anisotropic substrates.

Numerical results are compared with the exact analytical solutions for the special case in which air is a substrate material; excellent agreement is found.

### II. THEORY

Figure 1 shows the cross sections of the asymmetrical coplanar waveguide (ACPW) and the asymmetrical coplanar strip line (ACSL) to be analyzed. The substrate is a uniaxially anisotropic medium, whose optical axis is assumed to be inclined at an angle of  $\gamma$  measured from the x axis. The permittivity tensor of this anisotropic substrate is given by

$$\hat{\boldsymbol{\epsilon}} = \begin{bmatrix} \boldsymbol{\epsilon}_{xx} & \boldsymbol{\epsilon}_{xy} \\ \boldsymbol{\epsilon}_{xy} & \boldsymbol{\epsilon}_{yy} \end{bmatrix} \boldsymbol{\epsilon}_{o} \qquad (1)$$

where

10000000

a have a set of

And a way of the start of

A Start Carlo

上二 いたいちいし

Arrest and

$$\epsilon_{xx} = \epsilon_{\downarrow\downarrow} \cos^2 \gamma + \epsilon_{\downarrow} \sin^2 \gamma$$

$$\epsilon_{yy} = \epsilon_{\downarrow\downarrow} \sin^2 \gamma + \epsilon_{\downarrow} \cos^2 \gamma$$

$$\epsilon_{xy} = (\epsilon_{\uparrow\downarrow} - \epsilon_{\downarrow}) \sin \gamma \cos \gamma$$
(2)

where  $\epsilon_{11}$  and  $\epsilon_{\perp}$  are the relative permittivities, longitudinal and transverse to the optical axis, respectively. The conductors are assumed to be of zero thickness.

#### A. Variational Expression for the Line Capacitance of ACPW

The derivation of the variational expression for the line capacitance of ACPW (shown in Figure 1(a)) is based on an extension of the procedure followed for the symmetrical case [4], [5], [8], and is outlined below.

From a solution to Laplace's equation, the charge distribution on the conductor at y = 0 can be expressed in terms of the aperture field e(x) at y = 0 as

$$\sigma(\mathbf{x}) = \frac{-j\epsilon_o}{2\pi} \int \int_{-\infty}^{\infty} \alpha f(\alpha) \, e(\mathbf{x}') \, e^{j\alpha(\mathbf{x}'-\mathbf{x}')} \, d\mathbf{x}' \, d\alpha \tag{3}$$



(a) Asymmetrical Coplanar Waveguide (ACPW)



(b) Asymmetrical Coplanar Strip Line (ACSL)

Figure 1. Asymmetrical coplanar transmission lines.

$$W_i = b_i - a$$
 (i = 1, 2)  
 $S_1 = \pm (a + b_1)$   
2 2

12220000V

1995 CA

and where

$$f(\alpha) = \left(1 + \frac{1 + \epsilon_{c} \tanh(Kh \mid \alpha \mid)}{1 + \frac{1}{\epsilon_{c}} \tanh(Kh \mid \alpha \mid)}\right) \frac{1}{\mid \alpha \mid}$$

$$K = \sqrt{\frac{\epsilon_{xx}}{\epsilon_{yy}} - \left(\frac{\epsilon_{xy}}{\epsilon_{yy}}\right)^{2}}$$

$$\epsilon_{c} = \sqrt{\epsilon_{xx}} \frac{\epsilon_{yy}}{\epsilon_{yy}} - \frac{\epsilon_{xy}}{\epsilon_{yy}} \frac{1}{\epsilon_{yy}}$$
(4)

The total charge  $Q_o$  on the center strip  $|\mathbf{x}| < a$  can be expressed as follows:

$$Q_o = \int_{\frac{x_1}{2}}^{\frac{x_1}{2}} \sigma(x) \, dx \tag{5}$$

where  $x_1$  and  $x_2$  can be arbitrary values in the right slot  $a < x_1 < b_1$  and in the left slot  $-b_2 < x_2 < -a$ , respectively.

Multiplying (5) by  $e(x_1)$  and integrating over the right slot located at  $a < x_1 < b_1$ , we get

$$Q_{o}V_{o} = \int_{a}^{b_{1}} \left( \int_{x_{2}}^{x_{1}} \sigma(x) dx \right) dx_{1}$$
(6-a)

 $(-b_2 < x_2 < -a)$ 

Similarly,

$$-Q_{o}V_{o} = \int_{-\phi_{2}}^{-\alpha} \left| \int_{x_{2}}^{x_{1}} \sigma(x) dx \right| dx_{2}$$
(6-b)

 $(a < x_1 < b_1)$ 

where  $V_o$  is the potential difference between the center strip and the ground conductors, i.e.,

$$V_{u} = \int_{a}^{b_{1}} e(x) dx = -\int_{-b_{2}}^{b} e(x) dx$$
(7)

Substituting (3) into (6), subtracting (6-b) from (6-a), and rearranging the resulting expression, we obtain the line capacitance as follows

$$C = \frac{Q_o}{V_o}$$
(8)

$$=\frac{\int \int_{-\infty}^{\infty} \int_{a}^{\infty} e(x) F(\alpha; x \mid x') e(x') d\alpha dx' dx}{\left| \int_{a}^{b_{1}} e(x) dx \right|^{2}}$$

where the Green's function F is given by

I suggested the second weak weak and the suggest and

$$F(\alpha; x \mid x') = \frac{\epsilon_o}{\pi} f(\alpha) \cos \{\alpha(x' - x)\}$$
(9)

It can be verified that equation (8) has the stationary property and provides an upper bound to the line capacitance C. As expected, equation (8) reduces to (2) in [5] for the symmetrical case  $b_1 = b_2$ . It is also worthwhile to mention that equation (8), together with (9) and (4), suggests the transformation from the anisotropic case ( $\epsilon_{1:1}, \epsilon_{1:h}$ ) to the isotropic case ( $\epsilon_{c}, Kh$ ).

B. Variational Expression for the Line Capacitance of ACSL

The derivation of the variational expression for the line capacitance of ACSL shown in Figure 1(b) is quite similar to that of ACPW. In this case, the potential distribution  $\phi(x)$  on the strip surface y = 0 is the basic quantity as opposed to the charge distribution in the ACPW case. The potential distribution can be expressed in terms of the charge distribution  $\sigma(x)$  on the strip conductor by solving Laplace's equation. The expression is

$$\phi(\mathbf{x}) = \frac{1}{2\pi\epsilon_o} \int \int_{-\infty}^{\infty} g(\alpha) \,\sigma(\mathbf{x}') \, e^{\,j\,\alpha'\,\mathbf{x}'\,-\,\mathbf{x}\,\mathbf{x}'} \,d\,\alpha \tag{10}$$

$$g(\alpha) = \frac{1 + \epsilon_c \coth(Kh \mid \alpha \mid)}{1 + \epsilon_c^2 + 2\epsilon_c \coth(Kh \mid \alpha \mid)} \bullet \frac{1}{\mid \alpha \mid}$$
(11)

 $\phi(x)$  should be constant on the strip conductors, that is,

$$\phi(x) = \frac{V_o}{2}$$
  $(a < x < b_1)$  (12-a)

$$\phi(x) = -\frac{V_o}{2} \qquad (-b_2 < x < -a) \tag{12-b}$$

where  $V_o$  is the potential difference between the strip conductors. By multiplying (12) with  $\sigma(x)$  and integrating over the right strip  $(a < x < b_1)$  and the left strip  $(-b_2 < x < -a)$ , respectively, we obtain

$$\frac{V_o}{2} \int_a^{b_1} \sigma(x) dx = \frac{V_o Q_o}{2}$$

$$= \frac{1}{2\pi\epsilon_o} \int_a^{b_1} \int \int_{-\infty}^{\infty} \sigma(x) g(\alpha) \sigma(x') e^{j\alpha(x'-x)} dx' d\alpha dx$$
(13-a)

and

States and states and states

20.25.25.20

ANAL STAND STAND

$$\frac{-V_o}{2} \int_{-b_2}^{a} \sigma(x) dx = \frac{V_o Q_o}{2}$$

$$= \frac{1}{2\pi\epsilon_o} \int_{-b_2}^{a} \int \int_{-\infty}^{\infty} \sigma(x) g(\alpha) \sigma(x') e^{j \sigma' x' - x'} dx' d\alpha dx$$
(13-b)

where  $Q_o$  is the total charge on the strip conductor

$$Q_{a} = \int_{a}^{b_{1}} \sigma(x) dx = -\int_{-b_{2}}^{-a} \sigma(x) dx$$
(14)

The line capacitance of ACSL can be obtained from (13) and can be expressed as follows

$$\frac{1}{C} = \frac{V_{\circ}}{Q_{\circ}}$$
(15)

$$=\frac{\int \int \sum_{-\infty}^{\infty} \int_{a}^{\infty} \sigma(x) G(\alpha; x | x') \sigma(x') d\alpha dx' dx}{\left| \int_{a}^{b} \sigma(x) dx \right|^{2}}$$

where Green's function G is given by

$$G(\alpha; x \mid x') = \frac{1}{\pi\epsilon_o} g(\alpha) \cos \{\alpha(x'-x)\}$$
(16)

Equation (15) gives an upper bound to 1/C, hence, a lower bound to the line capacitance C.

## C. Method of Solution

States -

AND REAL PROPERTY AND INC.

The line capacitance can be evaluated by applying the Ritz procedure to the variational expressions (8) and (15). Taking the edge effect into account, the unknown aperture field e(x) in (8) and the unknown charge distribution  $\sigma(x)$  in (15) are expanded in terms of the appropriate basis functions as follows:

$$e(x) = \sum_{k=1}^{N_1} A_k^{(1)} f_k^{(1)}(x) + \sum_{k=1}^{N_2} A_k^{(2)} f_k^{(2)}(x)$$
(17-a)

$$\sigma(x) = \sum_{k=1}^{N_1} B_k^{(1)} f_k^{(1)}(x) + \sum_{k=1}^{N_2} B_k^{(2)} f_k^{(2)}(x)$$
(17-b)

$$f_{k}^{(i)} = \frac{T_{k} \left[ \frac{2(x - S_{i})}{W_{i}} \right]}{\sqrt{1 - \left\{ \frac{2(x - S_{i})}{W_{i}} \right\}^{2}}} \qquad i = 1,2$$

$$S_{1} = \pm (a + b_{1})/2, \qquad W_{1} = b_{1} - a$$
(18)

where  $T_{k}(y)$  are Chebyshev's polynomials of the first kind, and  $A_{k}^{(i)}$  and  $B_{k}^{(i)}$  are unknown coefficients which can be determined by substituting (17) into (8) and (15), and requiring

$$\frac{\partial}{\partial A_k^{(i)}} C = 0 \tag{19-a}$$

and

15555

WASSEL BUTTER REPORT

100000

Satasta.

$$\frac{\partial}{\partial B_k^{(i)}} \left( \frac{1}{C} \right) = 0 \quad , \tag{19-b}$$

respectively.

#### **III. NUMERICAL RESULTS**

In this section, the numerical results derived from the application of the Ritz procedure to the variational expressions for the line capacitance are presented. The accuracy of computation depends on the number of basis functions, i.e.,  $N_1$  and  $N_2$  in (17). Tables 1 and 2 show the numerical results of the line capacitance of ACPW and ACSL for different values of  $N_1$ ,  $N_2$ . The tables include the results for the special cases with air replacing the substrate material, i.e., for  $\epsilon_{11} = \epsilon_{-} = 1$ . This special case lends itself to an exact analytical solution via the use of a sequence of conformal transformations [Appendix I]. Note that the values of capacitance for ACPW, obtained by using (8), are slightly larger than the exact values (upper bounds) while those of ACSL are slightly smaller than the exact values (lower bounds). The convergence is seen to be very rapid for both the cases and for a wide range of parameters, as evidenced by the fact that very accurate results are obtained with only a small number of basis functions. Note that  $N_1 = N_2 = 2$  is sufficient in most cases except for extremely small values of  $a/W_1$  and large values of  $W_2/W_1$ . Even so,  $N_1 = N_2 = 3$  is sufficient for these extreme cases.

Figures 2 through 5 present numerical examples for the asymmetrical structures of both the ACPW and ACSL types. Figure 2 shows the effective dielectric constant  $\epsilon_{off}$  and the characteristic impedance  $Z_o$  as a function of the width ratio  $W_2/W_1$ , for ACPW with an isotropic dielectric substrate. The values for the symmetrical case  $(W_2/W_1 = 1)$  [4] are presented only as an indication of the accuracy of computation.

Figure 3 shows the characteristics of ACPW on an anisotropic sapphire substrate. The effective dielectric constant and the characteristic impedance are shown as a function of the inclination of the optical axis  $\gamma$ .

Figure 4 shows the variation in the characteristics of ACSL on an isotropic dielectric substrate with the width ratio  $W_2/W_1$ . The effective dielectric constant of ACSL becomes smaller as the width ratio  $W_2/W_1$  becomes larger in the same manner as the ACPW case; however, the characteristic impedance of ACSL becomes smaller as  $W_2/W_1$  becomes larger as opposed to the ACPW case.

TABLE 1
---------

والمراجة وبالمساد مشاهلة هراجي ويتراس

Line capacitance of ACPW  $C/\epsilon_{o}$ 

Without substrate

 $\varepsilon_{||} = \varepsilon_{||} = 1, \quad h = 0$ 

a/W <sub>1</sub>	W <sub>2</sub> /W <sub>1</sub>	N <sub>1</sub> 1 N <sub>2</sub> 1	2 2	3 3	Conformal mapping
	1	2.199	2.107	2.105	2.105
0.25	2	2.085	1.946	1.940	1.940
	4	2.085	1.858	1.838	1.836
	1	3.520	3.510	3.510	3.510
1.50	2	3.219	3.198	3.198	3.198
	4	3.005	2.956	2.956	2.956

With sapphire substrate

and the second second second

ε<sub>||</sub> = 11.6,  $\gamma = \pi/4$ ,  $h/W_1 = 1$ εI 9.4, W<sub>2</sub>/W<sub>1</sub> a/W<sub>l</sub> N<sub>1</sub> 1 2 3 4 1 2 3 N<sub>2</sub> 4 10.792 10.574 10.569 10.569 1 9.212 0.25 9.463 9.220 9.215 2 8.534 8.246 8.236 8.251 4 13.797 13.795 13.795 1 13.800 11.750 11.740 11.740 1.50 11.755 2 10.179 10.226 10.213 10.179 4

TA	BL	E.	2

Line capacitance of ACSL  $C/\epsilon_0$ 

Without substrate

 $\varepsilon_{\parallel} = \varepsilon_{\parallel} = 1, h = 0$ 

a/W1	W <sub>2</sub> /W <sub>1</sub>	<sup>N</sup> 1 <sup>N</sup> 2	1	2 2	3 3	Conformal mapping
	1	1	.819	1.899	1.901	1.901
0.25	2	1	.918	2.055	2.062	2.062
	4	1	.918	2.153	2.175	2.178
	1	1	.136	1.140	1.140	1.140
1.50	2	1	.243	1.251	1.251	1.251
	4	1	.331	1.353	1.353	1.353

With boron-nitride substrate

AND BARRIER MARRIER MANAGER (MARRIER AMANAME AMARRIER MARRIER ( ) STATES ( ) AMANAME .

 $\varepsilon_{||} = 5.12,$  $\gamma = \pi/4$ ,  $h/W_1 = 2$  $\varepsilon_1 = 3.40,$ 1  $W_2/W_1$ N<sub>1</sub> 2  $a/W_1$ 3 4 1 2 N<sub>2</sub> 3 4 1 4.513 4.752 4.757 4.757 4.624 5.075 0.25 2 5.057 5.076 5.252 4.383 5.176 5.246 4 2.586 2.586 1 2.569 2.586 2.759 2.760 2.760 1.50 2 2.719 4 2.778 2.886 2.890 2.890



Y Cara Start



Figure 3. ACPW on anisotropic sapphire substrate.



۰. 

Sec. 1

Figure 4. ACSL on isotropic dielectric substrate.



Figure 5. ACSL on anisotropic boron-nitride substrate.

Figure 5 shows the variation in the effective dielectric constant and the characteristic impedance of ACSL on an anisotropic boron-nitride substrate with the width ratio  $W_2/W_1$ .

1. 2. C. F.

### **IV. CONCLUSIONS**

In this paper, the variational expressions for the line capacitance of the asymmetrical coplanar waveguide (ACPW) and the asymmetrical coplanar strip line (ACSL) have been derived. An efficient computational scheme, based on the Ritz procedure, has been employed for the numerical computations. Numerical results have been compared with the exact analytical solutions for the special case of air as the substrate material and excellent agreement has been found for a wide range of parameters. Also, some numerical data for ACPW and ACSL are shown for both the isotropic and anisotropic substrates.

The analytical approach presented herein is quite general and is easily applicable to other structures, such as asymmetrically coupled microstriplines.

1000000

1. N. N. N.

## APPENDIX I

# ASYMMETRICAL COPLANAR WAVEGUIDE AND ASYMMETRICAL COPLANAR STRIP LINE WITHOUT SUBSTRATE

The line capacitances of the asymmetrical coplanar waveguide (ACPW, Fig. 6(a)) and the asymmetrical coplanar strip line (ACSL, Fig. 7(a)) without substrates can be evaluated analytically by a repeated application of conformal mapping. A series of transformations for ACPW and ACSL are shown in Figs. 6 and 7, respectively. The determinantal equations for the ratio  $t_3/u_3$  and  $s_3/t_3$ , which determine  $k_3$ , are given in the following:

the determinantal equation of  $t_3/u_3$ 

$$2 \frac{K(k_o)}{K'(k_o)} = \frac{K \left[\frac{t_3}{u_3}\right]}{K' \left[\frac{t_3}{u_3}\right]}$$
(A-1)

the determinantal equation of  $s_3/t_3$ 

for ACPW

$$\frac{F(\arcsin\frac{p_o}{q_o}, k_o)}{K(k_o)} + 1 = 2 \frac{F(\arcsin\frac{s_3}{t_3}, \frac{t_3}{u_3})}{K\left(\frac{t_3}{u_3}\right)}$$
(A-2)

for ACSL

いたが、「

1. 2. Car 2. Car



Figure 6. A series of transformations for the asymmetrical coplanar waveguide without substrates.















----- Magnetic Wall



$$\frac{F(\arcsin\frac{q_o}{r_o}, k_o)}{K(k_o)} - 1 = 2 \frac{F(\arcsin\frac{s_3}{t_3}, \frac{t_3}{u_3})}{K\left(\frac{t_3}{u_3}\right)}$$
(A-3)

where F(a,b) is the elliptic integral of the first kind and K(k) is the complete elliptic integral of the first kind.

#### REFERENCES

- C. P. Wen, "Coplanar waveguide: A surface strip transmission line suitable for nonreciprocal gyromagnetic device applications," *IEEE Trans. Microwave Theory Tech.*, (1969 Symposium Issue), vol. MTT-17, pp. 1087-1090, December 1969.
- J. B. Knorr and K. D. Kuchler, "Analysis of coupled slots and coplanar strips on dielectric substrates," IEEE Trans. Microwave Theory Tech., vol. MTT-23, pp. 541-548, July 1975.
- 3. Y. Hayashi, T. Kitazawa and S. Sasaki, "Analysis of coplanar strip lines on an anisotropic substrate using Galerkin's method," *Trans. IECE Japan*, vol. 64-B, no. 7, pp. 666-673, July 1981.
- T. Kitazawa and Y. Hayashi, "Coupled slots on an anisotropic sapphire substrate," *IEEE Trans.* Microwave Theory Tech., vol. MTT-29, pp. 1035-1040, October 1981.
- T. Kitazawa and Y. Hayashi, "Quasi-static characteristics of coplanar waveguide on a sapphire substrate with its optical axis inclined," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 920-922, June 1982.
- 6. M. Kitlinski and B. Janiczak, "Dispersion characteristics of asymmetric coupled slot lines on dielectric substrates," *Electron. Lett.*, vol. 19, pp. 91-92, February 1983.
- 7. I. Kneppo, J. Cotzman and D. Cesta, "Basic parameters of nonsymmetrical coplanar line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 718, August 1977.
- 8. T. Kitazawa and R. Mittra, "Quasistatic characteristics of coupled coplanar-type transmission lines," submitted for publication.

