

selective etchant. The later growth stages have been reported previously.^{5,6}

The wafer was then cleaved into 500 μm long devices, which were bonded *p*-side down, using AuSn solder, on to diamond heatsinks mounted on copper submounts.

Device characteristics: The dependence of the optical output power on increasing CW drive current of a typical 500 μm long device is shown in Fig. 2. The CW output power per facet is in excess of 20 mW at 25°C with a threshold current of 26 mA. The temperature dependence, T_0 , of the pulsed threshold current was measured to be 45 K, over the temperature range 15 to 60°C. Devices had a lasing wavelength of 1.55 μm , and a spectral width of under 5 nm (FWHM). Devices with improved characteristics have been fabricated, and these will be reported when sufficient lifetest data has been accumulated.

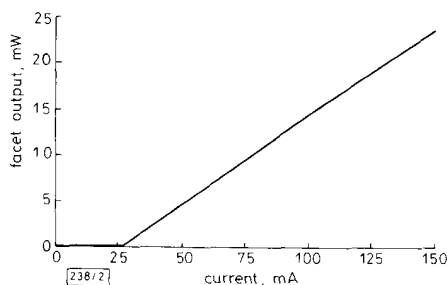


Fig. 2 Optical output power from one facet against CW bias current
Uncoated 500 μm long GRINSCH MQW laser device

Reliability performance: It has been shown that BH lasers can exhibit two distinct stages of degradation.^{7,8} There is a relatively rapid first stage which saturates, followed by a much lower rate of long-term wearout.

The GRINSCH laser devices which are the subject of this letter were subjected to a burn-in of 100 mA drive current at 125°C for 24 h, to complete the changes associated with the first stage of degradation. A batch of ten GRINSCH lasers have been on lifetest for 3500 h at a constant output power of 4 mW per facet at 50°C. From an initial current, I_0 , the increase bias current, I , necessary to maintain this output over time was monitored. Fig. 3 shows the normalised bias current, I/I_0 , against the lifetest duration in hours. The average rate of increase of drive current is 1%/kh. These initial results for GRINSCH MQ lasers are very encouraging. We considered

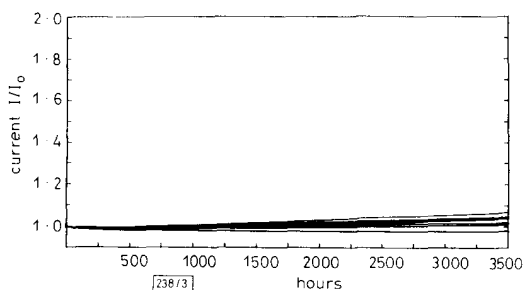


Fig. 3 Normalised bias current against time
Constant optical power output of 4 mW at 50°C
Ten uncoated 500 μm long GRINSCH MQW lasers

the risks to the reliability to be from two principal sources. These are the interfaces, where the defects may be localised, and the lattice mismatch between the layers, which might give rise to subsequent defect propagation. The absence of early failures on lifetest for this relatively complex structure, and the encouragingly low degradation rate, suggests that the interfaces are of a good quality, and good control of the lattice parameters has been achieved.

Conclusions: We have fabricated the first reliable GRINSCH MQW lasers grown entirely by MOVPE, with projected rates of degradation which are promising for such a relatively complex structure.

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References

- LAU, K. Y., DERRY, P. L., and YARIV, A.: 'Ultimate limit in low-threshold quantum well GaAlAs semiconductor lasers', *Appl. Phys. Lett.*, 1988, **52**, pp. 88-90
- TAKANO, S., SAKI, T., YAMADA, H., KITAMURA, M., MITO, I., and SUZUKI, T.: 'Improvements in resonance frequency and T_0 value by 1.5 μm InGaAs MQW lasers grown by MOVPE', *J. Cryst. Growth*, 1988, **93**, pp. 857-862
- WESTBROOK, L. D., FLETCHER, N. C., COOPER, D. M., STEVENSON, M., and SPURDENS, P. C.: 'Intensity noise in 1.5 μm InGaAs quantum well buried heterostructure lasers', *Electron. Lett.*, 1989, **25**, pp. 1123-1124
- COOPER, D. M., SELTZER, C. P., AYLETT, M., ELTON, D. J., HARLOW, M., WICKES, H., and MURRELL, D. L.: 'High-power 1.5 μm all-MOVPE buried heterostructure graded-index separate-confinement multiple-quantum-well lasers', *Electron. Lett.*, 1989, **25**, pp. 1635-1636
- COOPER, D. M., COLE, S., DEVLIN, W. J., HOBBS, R. E., NELSON, A. W., REGNAULT, J. C., SKEATS, A. P., SIM, S. P., and SPURDENS, P. C.: 'High-performance, high-reliability buried heterostructure lasers by MOVPE', *Electron. Lett.*, 1988, **24**, pp. 519-521
- SELTZER, C. P., BURNES, A. L., STEVENSON, M., HARLOW, M. J., COOPER, D. M., REDSTALL, R. M., and SPURDENS, P. C.: 'Reliable 1.5 μm buried heterostructure, separate-confinement, multiple quantum well (BH-SC-MQW) lasers entirely grown by metalorganic vapour-phase epitaxy (MOVPE)', *Electron. Lett.*, 1989, **25**, pp. 1449-1450
- SIM, S. P.: 'A review of the reliability of III-V opto-electronic components', *Proc. Nato Advanced Workshop on Semiconductor Device Reliability*, 4th-9th June 1989, pp. 301-326
- HIRAO, M., MIZUSHI, K., and NAKAMURA, M.: 'High-reliability semiconductor lasers for optical communications', *IEEE J. Sel. Areas Commun.*, 1986, **SAC-4**, pp. 1494-1500

STATISTICAL AR MODELS FOR THE FREQUENCY SELECTIVE INDOOR RADIO CHANNEL

Indexing terms: Radiowave propagation, Modelling

A statistical model of the indoor radio channel is proposed that is derived from a second order autoregressive process representation of the channel frequency response. The accuracy of the statistical model is examined by comparing the cumulative distribution functions of the RMS delay spread and the 3 dB width of the frequency correlation function computed from the regenerated data with that of the measurements performed in two indoor radio propagation studies in the 0.9-1.1 GHz band.

Introduction: In previous letters by the authors, frequency domain measurements of the indoor radio channel were described¹ and it was shown that they can be modelled as a second order autoregressive (AR) process.² The location of the poles of the model in the *z*-plane was further related to the arrival of two clusters of paths.² In this letter, based on the statistical variations of the poles obtained from the frequency domain measurements reported in Reference 1, several models

to regenerate the frequency domain characteristics of the channel with a computer simulation are examined.

It is shown that the cumulative distribution functions (CDFs) of the 3 dB width of the frequency correlation function and the RMS delay spread of the channel resulting from these models closely match the CDFs of the actual measurements. The frequency domain models use fewer statistical parameters than the time domain models.^{3,4} They can therefore be simulated on the computer with considerable ease. The data base used for the confirmation of the results consists of 70 frequency domain measurements performed at the IBM office in the sixteenth floor of the thirty two storey Shawmut Bank building in downtown Worcester and 58 measurements at the second floor of the three storey Atwater Kent Laboratories at the Worcester Polytechnic Institute.¹ In each of the sites, the receiver is fixed in a central location and the transmitter is moved to different locations in a picocell (less than 50 m in diameter) to take the measurements.

Statistical models for the AR parameters: Assuming that the frequency response of the channel forms a second order AR process,² the n th sample of a measured frequency response of the channel f_n will be represented by

$$f_n = a_1 f_{n-1} + a_2 f_{n-2} + u_n$$

where a_i s are the coefficients of the AR model and u_n is the white noise driving the process. In the wideband frequency domain measurements used,¹ the distance between the two samples of the frequency response 0.25 MHz and the measurements cover a 200 MHz band of 0.9–1.1 GHz.

Taking the z-transform of the above equation we have

$$\begin{aligned} G(z) &= \frac{F(z)}{U(z)} \\ &= \sum_{i=1}^2 \frac{1}{1 - a_i z^{-1}} \\ &= \prod_{i=1}^2 \frac{1}{(1 - p_i z^{-1})} \end{aligned}$$

where the p_i s represent the poles of the process. Using this concept, statistical modelling of the channel is reduced to the statistical characterisation of the two poles of the model and the variance of the driving white noise process. Table 1 presents the mean, variance and the range of the magnitude and angle of the two poles obtained from measurements in the IBM office and the WPI campus.

In the models introduced in this letter, it is assumed that the random parameters used to represent the magnitude or the phase of the poles are statistically independent Gaussian random variables defined in a certain range. The mean, variance and range of each value is determined from the empirical data for each experiment. The angle of the first pole representing the arrival of the first cluster² is normalised to the arbitrary value of -18° which corresponds to the first cluster being centred at 200 ns. The angle of the second pole is adjusted to maintain the original angular difference. The normalisation will reduce the complexity of the modelling. It does not affect the frequency selective fading multipath characteristics of the channel.

Model 1 assumes the magnitude and the phase of the second pole and the magnitude of the first pole are all Gaussian random variables. For model 2, the angle of the second pole is assumed fixed at the average angle of all measurements and the magnitude of the two poles are treated as random variables. Model 3 assumes the angle and the magnitude of the second pole are fixed at the average angle and the average magnitude of the measurements and only the magnitude of the first pole is considered as a random variable. Model 4 assumes both poles are fixed at the average magnitude and angle of the poles observed in an experiment. These models reflect the relative importance of the location of the first and the second pole on the modelling of the behaviours of the channel.

The magnitude of pole 1 has smaller variations than the magnitude of pole 2 for the experiments. This indicates that the first cluster is more predictable than the second cluster. To relate the RMS delay spread with the location of the poles, the correlation between these parameters is calculated. The correlation of the magnitude of pole 1 with the 3 dB width of the frequency correlation function and the RMS delay spread reveals high values; so as pole 1 gets closer to the unit circle the RMS delay spread decreases and the 3 dB width increases. In contrast, the magnitude or angle of pole 2 shows weak correlation with the 3 dB width of the correlation function and the RMS delay spread of a profile.

For the purpose of modelling, it is desirable to know the probability distribution of the gain of the AR process for each of the experiment sites. To determine this probability distribution, the cumulative distribution function (CDF) of the received powers for all measurements of an experiment is compared with the theoretical CDFs for log-normal, Weibull and Rayleigh probability distributions. The log-normal probability distribution provides the best fit. The measured mean and variance of the distribution were 0.0091 and 0.0267, respectively for the IBM experiment, and 0.0098 and 0.0357, respectively, for WPI.

Results of computer simulation: The mean, the variance and the ranges provided in Table 1 were used to generate the two

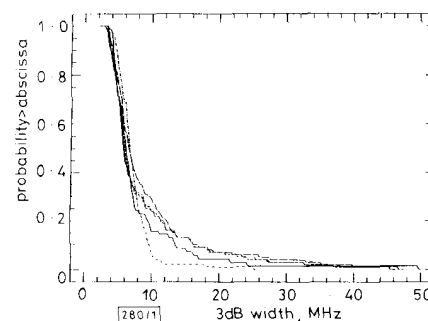


Fig. 1 CDFs of 3 dB width
— IBM
..... model 1
----- model 2
- . - . - model 3
- - - - - model 4

Table 1 STATISTICS OF THE LOCATION OF THE FIRST TWO POLES FOR THE IBM AND WPI EXPERIMENTS

Experiment	Parameter	Average	Standard deviation	Minimum	Maximum
IBM	$ p_1 $	0.9871	0.006832	0.9648	0.9982
	$\text{ang}(p_1)$	-18.82	1.989	-22.75	-14.73
	$ p_2 $	0.8380	0.08995	0.5701	0.9780
	$\text{ang}(p_2)$	-6.355	1.355	-9.376	-2.459
WPI	$ p_1 $	0.9878	0.005093	0.9750	0.9986
	$\text{ang}(p_1)$	-19.04	1.839	-22.44	-14.94
	$ p_2 $	0.8624	0.07776	0.6224	0.9599
	$\text{ang}(p_2)$	-8.239	1.477	-9.213	-3.549

poles for each of the four models. The poles were then used to form the AR process. The variance of the noise driving the process is determined from a log-normal distributed random variable with the variance and mean obtained from measurements in that area.

Fig. 1 is a graph of the CDF of the 3dB width of the frequency correlation function that resulted from 100 simulated measurements for each of the four models for the IBM office, and the actual CDF from the 70 measurements. Fig. 2 is similar to Fig. 1 for the RMS delay spreads. The results of the frequency domain characteristics (3dB width of the frequency correlation function) are closer than the time domain characteristics (RMS delay spread). This is because of the fact that frequency correlation information is used for the AR modelling. The first three models provide very close fits for the frequency domain characteristics. The simpler model 4 provides smaller variations of RMS delay spread than the other three models. Though the buildings used for the experiments are completely different, the statistics of the parameters of the model and consequently the time and the frequency domain characteristics of the two environments are very close.

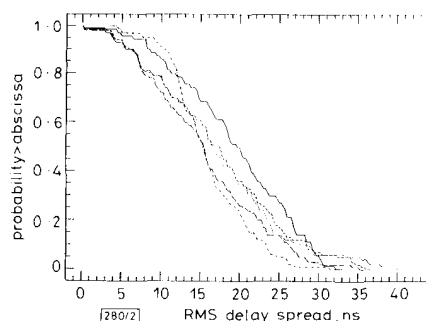


Fig. 2 CDFs of RMS delay spread

Summary and conclusions: Four statistical models for the parameters of the AR model were examined. It was shown that, for the two sets of measurements considered in this letter, the CDFs of the 3dB width of the frequency correlation function and the RMS delay spread of the measured data and the CDFs generated from the models 1, 2 and 3 were in close agreement. The most dominant parameter of the modelling was shown to be the magnitude of the first pole.

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References

- PAHLAVAN, K., and HOWARD, S. J.: 'Frequency domain measurements of the indoor radio channels', *Electron. Lett.*, 1989, **25**, pp. 1645-1647
- HOWARD, S. J., and PAHLAVAN, K.: 'Autoregressive modelling of the indoor radio channel', *Electron. Lett.*, 1990, **26**, (12), pp. 810-812
- SALEH, A. A., M., and VALENZUELA, R. A.: 'A statistical model for indoor multipath propagation', *IEEE J. Selected Areas Commun.*, 1987, **SAC-5**, pp. 128-137
- GANESH, R., and PAHLAVAN, K.: 'On the modeling of fading multipath indoor radio channels', *Proc. IEEE GLOBECOM'89*, Dallas, TX, 30th Nov. 1989, pp. 1346-1350

ANALYSIS OF EDGE SLOTS IN RECTANGULAR WAVEGUIDE USING FINITE-DIFFERENCE TIME-DOMAIN METHOD

Indexing terms: Waveguides, Numerical methods

A finite-difference time-domain (FD-TD) method for analysing edge slots in rectangular waveguides is suggested. The proposal is supported by an example.

Introduction: Inclined slots in the narrow wall of rectangular waveguides (edge slots) have been widely used in the realisation of antenna arrays. Most of these designs have been based on an experimental determination of the slot properties. The moment method has been applied to obtain a numerical solution of the integral equation formulation for the self-properties of longitudinal slots in the broadwall of rectangular waveguide.¹ Such analyses assume that the slot radiates through an infinite groundplane for the exterior problem. For the edge slot such arguments are less cogent, and the absence of an appropriate Green's function for a source radiating in the presence of a conducting rectangular cylinder has prevented the direct numerical solution of the edge slot problem. A variational treatment for determining the self-admittance of such edge slots has recently been presented,² and represents an important step in the solution of the problem. Although slot wrap-around is accounted for in an approximate manner in the above analysis (as it must be to be of any use at all), the waveguide is assumed to have zero thickness walls and a particular form for the electric field distribution in the slot is assumed. The slot self-properties are sensitive to both these factors.

In this letter we apply the monochromatic finite-difference time-domain (FD-TD) method to determine the properties of the edge slots. Such a differential equation based method obviates the need for the above-mentioned Green's function. No assumptions need be made as to the functional form of the field in the slot. The wall thickness effects are automatically included. The resolution assigned to these unknowns are limited only by the mesh density selected.

Formulation: The numerical sampling region over which the FD-TD lattice is established consists of the interior waveguide region around the slot, and a portion of 'free space' exterior to the waveguide, situated adjacent to the slot. Appropriate absorption boundary conditions are used at the lattice truncation planes interior to the waveguide³ at which the slot network scattering properties are computed. On the boundary surface of the exterior sampling region free-space absorbing boundary conditions are utilised.⁴ Being a differential equation based method, the FD-TD mesh is easily tailored (by an alteration of input data only) to accommodate arbitrary geometries (e.g., the edge slot).

Discussion of computational requirements and supportive results: The dimensions of the slot analysed are identical to those in Figs. 9-12 of Reference 5. With the limited memory capacity available to the present authors the cubed cell size was 0.5 mm on a side. This meant that only three cells could be fitted along the transverse slot dimension, with a 'staircase' approximation along the length of the slot. The exterior sampling region used was of rectangular shape, out to a distance of 10 mm from the slot radiating surface, and 15 mm away from the slot in the direction of the waveguide axis. The interior sampling region lattice truncation planes were 15 mm on either side of the centre of the slot, which is sufficient.³ Except for the interior sampling region, the above is a fairly coarse discretisation, and would not be used to determine data to be used for antenna design purposes. More cells should be used to both properly resolve the slot geometry and permit the field in the slot to be correctly approximated. Furthermore, the exterior sampling region boundary should be at least 3λ away from the slot.

With the sampling region used for the results given here there were already 252 000 cells representing approximately