

of 30 Ω was measured for 15 μm -diameter devices fabricated by the implant isolation technique (see Fig. 1; the implant condition will be stated later) or the etched mesa technique.⁴

While the all-epitaxially grown VCSEL structure outlined above already permits greatly simplified fabrication and testing, the use of implant isolation further enhances this feature. After the growth, 15 μm -diameter Ag(1000 Å)/Au (1000 Å) contacts were defined by evaporation and liftoff. Photoresist was then used to cover the circular contacts to prevent ion penetration into the devices during oxygen implantation. A two-step implant process was employed ($1 \times 10^{14} \text{ cm}^{-2}$ dose at 180 kV, followed by $3 \times 10^{13} \text{ cm}^{-2}$ dose at 80 kV) to ensure a uniform implant profile to a depth of $\sim 0.7 \mu\text{m}$, as indicated in the dotted region in Fig. 1. Singly charged oxygen species were used.

As shown in Fig. 1, the etched hole in the substrate allows light transmission. However, for wafer-scale testing of the lasing threshold of the VCSELs (without being diced into individual chips), it is sufficient and convenient to collect the light from the top surface of the device (*p*-side) diffracted and/or scattered out of the implant-defined mesas. Pulse widths of 30 ns to 1 μs with a duty cycle up to 20% were used.

The emission spectral characteristics of the VCSEL fabricated by implant isolation were found to have similar properties to those reported previously⁴ fabricated by the etched-mesa isolation technique. In both cases, the VCSEL emission spectrum, when biased below the lasing threshold, showed a broad background with the superposition of a narrow peak. The broad background reflected the gain spectrum of the active material. The narrow peak was due to the cavity resonance enhanced emission and was about $\sim 5 \text{ \AA}$ wide. Above the threshold, the cavity mode reduced to a resolution-limited 2–3 Å linewidth and its intensity dominated. Fig. 2 shows a typical room-temperature lasing spectrum of the implant-isolated VCSEL with a 0.5 μm active layer pulsed at $I = 45 \text{ mA}$ ($1.1 I_{\text{th}}$). Single longitudinal mode emission is seen, and the peak/background ratio is greater than 30 dB.

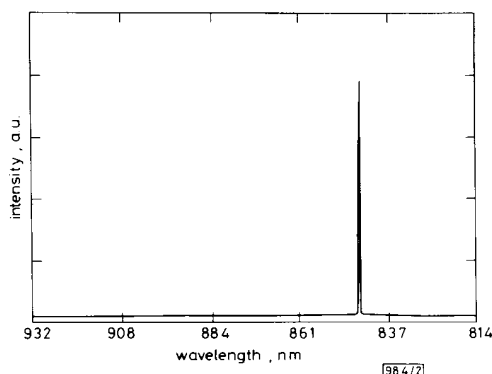


Fig. 2 Room-temperature pulsed emission spectrum from implant-isolated device with 0.5 μm active layer

Room-temperature pulsed threshold current for this device was 40 mA, and spectrum was taken at 45 mA

Similar light output/current (L/I) characteristics were also obtained for the VCSEL fabricated by the two methods. A sharp increase in the slope of the L/I curve occurred at a threshold current value. In the wafer with 0.25 μm active layer thickness, room-temperature pulsed threshold currents for implant-isolated 15 μm -diameter devices ranged from 26 to 37 mA with corresponding wavelengths ranging from 863 to 854 nm. The variation in the lasing wavelength was due to the nonuniform layer thickness across the wafer. In the wafer with 0.5 μm active layer thickness, the room-temperature pulsed threshold current ranged from 30 to 50 mA. To within our experimental error, the implant isolation results were identical to those for etched mesa devices.

Quantitative studies on the implant conditions for optimising device isolation and on the long-term stability are now under investigation. It seems that the parameter space for effective isolation of the VCSELs is rather large, indicating the

implant isolation is a viable approach to VCSEL fabrication. The use of this technique greatly simplifies the fabrication process, and yields a planar device which will circumvent many problems associated with the use of these devices in integrated structures and other sophisticated applications.

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FREQUENCY DOMAIN MEASUREMENTS OF INDOOR RADIO CHANNELS

Indexing terms: Radiowave propagation, Radiocommunication

Frequency responses of the indoor radio channel for 128 locations in an office and a research laboratory are analysed. Some statistics on the number of fades are determined. The cumulative distribution function (CDF) of the 3 dB bandwidth of the frequency correlation function is presented, and experimental results relating the RMS delay spread of the channel and the inverse of the 3 dB width of the frequency correlation function are given.

Introduction: The reported wideband measurements and models for the indoor radio channels have been performed almost exclusively in the time domain.^{1–5} One exception was the limited measurement reported in Reference 5, where the changes in the frequency response when an object moves close to the transmitter or the receiver were illustrated. This letter presents some frequency domain statistics of the indoor radio channel and relates the results to the time domain statistics.

Coherent wideband frequency domain measurements, presented in this letter, provide the magnitude and phase of the

frequency response of the channel. As a result, the exact time domain response can also be obtained by taking the inverse Fourier transform of the measured data. The wideband time domain measurements in References 1-5 provide only the magnitude of the time domain response. The transmitted power in the frequency domain measurement is constant as opposed to the time domain measurement where the ratio of the peak to average transmitted power is large. This fact allows a larger area to be measured and reduces the effects of nonlinearities. Also, the set-up is easier and the measurement time is shorter in the frequency domain as compared with the time domain measurements explained in References 1 and 2.

Measurements: The heart of indoor radio measurements in the frequency domain is a network analyser which outputs a swept frequency signal and analyses the received signal. The signal generated by the network analyser is used as the input to a 45 dB transmitter RF amplifier. The output of the RF power amplifier is propagated by a dipole antenna. The signal from the receiver dipole antenna is passed through an attenuator and a series of amplifiers with a gain of 60 dB. The output of the amplifiers is returned to the network analyser to determine the frequency and time response of the channel. The measured data are then read and stored by the PC controller for further analysis.

The statistics presented are obtained from 128 different locations in two buildings. The first set of measurements are obtained from the IBM office, located at the 16th floor of the 32-storey Shawmut Bank building in downtown Worcester, MA. The receiver was placed in a central location and the transmitter was moved to different locations for each frequency response measurement. The office consisted of a central open area surrounded by small offices. A total of 70 frequency responses were collected. They were divided into two groups, 46 mobile and 24 fixed. Fixed measurements were taken from locations where data transmission devices such as a terminal existed. Mobile measurements were taken from locations where data transmission by portable phone would occur, such as the middle of a room or areas close to desks.

The second set of measurements were taken on the second floor of the 3-storey Atwater Kent Laboratories at the Worcester Polytechnic Institute. The receiver was placed in the central computer terminal room. Measurements from 58 locations close to computer terminals in the same room, adjacent laboratories, a power systems laboratory across a hallway, and offices across another hallway were taken.

Analysis of data: Fig. 1 shows a plot of the magnitude and phase of a typical frequency response $H(f, x)$ measured at a location x , and the corresponding magnitude of the time domain response $|h(\tau, x)|$. The magnitude of the frequency response in decibels, the phase of the frequency response in degrees, and the magnitude of the time response on a linear scale are shown. The frequency response consists of 801 complex samples at a frequency spacing of 0.25 MHz for a frequency span of 200 MHz, which is centred at 1 GHz. From this frequency response a time response of 4000 ns duration can be derived. The time response is truncated to show only that portion with any significant energy. The frequency selective fading nature of the channel is seen to result in deep fades at certain frequencies. The phase is linear for most parts, except for those frequencies in deep fade for which a phase hit is observed. The time domain response illustrates the multipath propagation which causes the frequency selective fading.

The number of fades below 10, 20 and 30 dB associated with each frequency response is determined. Table 1 presents the average of the number of fades over all frequency responses, and minimum and maximum number of fades observed in any frequency response. Considering these numbers, one would expect to observe an average of one fade of greater than 10, 20 and 30 dB every 13, 42 and 135 MHz, respectively, for a given location.

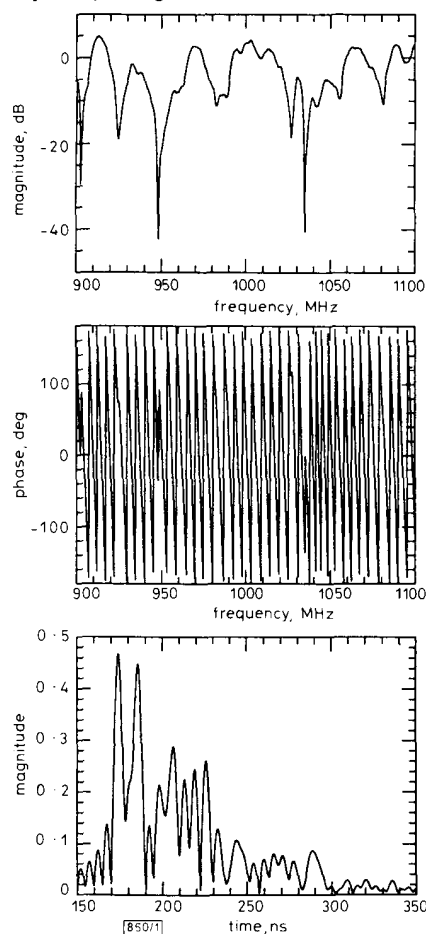


Fig. 1 Example of measurement from one location made with network analyser

Top is magnitude of frequency response in dB; middle is phase of frequency response in degrees; bottom is magnitude of inverse Fourier transform of frequency response

The 3 dB width of the magnitude of the complex autocorrelation function of the frequency response, which is defined as

$$R(\Delta f, x) = \int H(f, x) H^*(f + \Delta f, x) df \quad (1)$$

Table 1 MINIMUM AND MAXIMUM NUMBER OF FADES FOR ANY LOCATION AS WELL AS AVERAGE NUMBER OF FADES OVER ALL LOCATIONS FOR GIVEN THRESHOLD

Location	Number of fades > 10 dB			Number of fades > 20 dB			Number of fades > 30 dB		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
IBM fixed	3	14.21	23	1	4.75	11	0	1.42	5
IBM mobile	0	13.98	27	0	4.45	11	0	1.30	5
WPI	0	16.60	27	0	5.03	14	0	1.71	8

was measured for all locations. This width is a measure of the similarity or coherence of the channel in the frequency domain, which is inversely proportional to the multipath spread of the channel. Fig. 2 shows the cumulative distribution function (CDF) of the 3 dB widths for the three measurement sets; fixed and mobile measurements at the IBM office, and the set at WPI. The measurements at WPI had smaller 3 dB widths. The results for fixed and mobile terminals at the IBM office were very close.

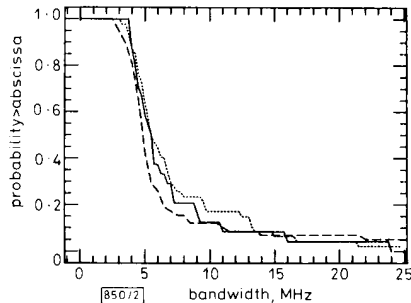


Fig. 2 Cumulative distribution function of 3 dB widths for three sets of measurements

— IBM fixed IBM mobile ---- WPI

From the corresponding time responses, the RMS delay spread is computed, which is a measure of the duration of the multipath.^{1,2} Fig. 3 shows the RMS delay spread against the inverse of the 3 dB width of the frequency correlation function obtained from experimental data from measurements in SECFL. The minimum mean-square error (MMSE) line fitting these data is also shown in this Figure. For the three measurement sets, the slope of the MMSE line was 0.15.

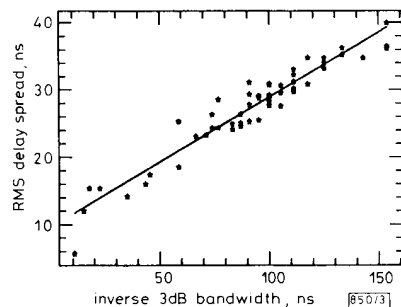


Fig. 3 Scatter plot of 3 dB widths against inverse of RMS delay spreads for each location of IBM fixed locations measured

Also shown is line with least mean-square error fitted to data (SECFL)

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REALISATION OF 2D ANALOGUE FILTERS

Indexing terms: Filters, 2D filters, Video, Image processing, Television

A modified method is presented for the realisation of 2D analogue filters used for processing television images. The proposed procedure reduces the required number of integrators considerably. For example, for the second- and third-order cases, the reduction in the number of integrators would be 7 and 21, respectively.

Recently a new method has been proposed for the realisation of 2D analogue filters used for processing video signals.¹ In this method the filter transfer function $H(s, z)$ is represented as

$$H(s, z) = \frac{\sum_{i=0}^N \sum_{j=0}^N a_{ij} s^{-i} z^{-j}}{1 + \sum_{i=0}^N \sum_{j=0}^N b_{ij} s^{-i} z^{-j}} \quad (1)$$

$$= \frac{Y(s, z)}{X(s, z)}$$

Eqn. 1 can be rewritten as

$$Y(s, z) = \sum_{i=0}^N \sum_{j=0}^N a_{ij} X(s, z) s^{-i} z^{-j} - \sum_{i=0}^N \sum_{j=0}^N b_{ij} Y(s, z) s^{-i} z^{-j} \quad (2)$$

For a 2×2 filter, the 'line' recursive equation can be written as

$$Y'(s, nT) = Y_0(s, nT) + Y_1(s, n-1T) + Y_2(s, n-2T) \quad (3)$$

where

$$Y_0(s, nT) = \sum_{i=0}^2 a_{i0} X(s, nT) s^{-i} - \sum_{i=1}^2 b_{i0} Y'(s, nT) s^{-i}$$

$$Y_1(s, n-1T) = \sum_{i=0}^2 a_{i1} X(s, n-1T) s^{-i} - \sum_{i=0}^2 b_{i1} Y'(s, n-1T) s^{-i}$$

$$Y_2(s, n-2T) = \sum_{i=0}^2 a_{i2} X(s, n-2T) s^{-i} - \sum_{i=0}^2 b_{i2} Y'(s, n-2T) s^{-i}$$