These equations show that the net threshold gain \( g_n L \) is identical for single and coupled DFB lasers provided that the unit cavity length is identical. The calculated axial mode intensity distributions for the two structures are also shown in Fig. 1, which also includes schematic diagrams of the propagating waves inside the cavity. Only those closed loops shown in the Figure fulfil the positive feedback condition for the lowest-order mode. The peak intensity inside the cavity for the structure in Fig. 1a is the same as for that in Fig. 1b with a doubled \( KL \)-value. The above features indicate that the cavity length can be doubled without changing the \( \kappa \)-value and without increasing the spatial hole burning effect by using the coupled phase-shift DFB structure. We can thus expect a long-cavity laser with a stable mode and a narrow emission linewidth.

The effect of spatial hole burning on the mode stability is now analysed following the procedure of Reference 7. The spatially inhomogeneous carrier distribution \( n(x) \) is obtained using the rate equation under the assumption that the oscillating mode field is initially unperturbed. This carrier distribution causes refractive index inhomogeneity along the cavity axis \( x \), which gives rise to changes in the axial mode field distribution and also the threshold gain \( g_n \). The change in \( g_n \) is estimated by linear perturbation theory of the coupled mode equation. As a result, the lowest-mode \( g_n \)-value increases with the injection current, while that for one of the two next-higher-order modes decreases. When the hole burning is strong enough, the \( g_n \)-value for the lowest mode crosses over that for the next-higher-order mode at a normalised injection current density \( J_{\text{max}} \), which defines the highest current limit for stable single-mode operation and thus the narrowest achievable linewidth \( \Delta \nu_{\text{m}} \) in eqn. 1.

Calculated \( \Delta \nu_{\text{m}} \) values are shown in Fig. 2 for the coupled phase-shift DFB laser as a function of the cavity length \( L \).

![Fig. 2 Linewidth calculated for 1-55 µm GaInAsP DFB lasers as a function of cavity length](image_url)

Thin solid lines show linewidth values for different injection current levels. Thick broken line and thick solid line show the minimum linewidth calculated taking into account spatial hole burning effect for single \((KL = 1.25)\) and coupled \((KL = 2.5)\) phase-shift DFB lasers, respectively.

Typical 1-55 µm GaInAsP material parameters and the linewidth enhancement factor \( \alpha = 5-4 \) were used in calculating the \( K \)-value in eqn. 1. Other parameters used were \( g_n = 20 \text{ cm}^{-1} \), \( \Gamma = 0.2, d = 0.13 \mu m \) and \( w = 5 \mu m \). The thick broken line is the lowest \( \Delta \nu \) limit for the single phase-shift DFB laser while the thick solid line is that for the coupled phase-shift DFB laser, both determined by the spatial hole burning effects as mentioned above. For the single and coupled phase-shift DFB structures, we used the \( KL \)-values of 1.25 and 2.5, respectively. The \( KL \)-value of 1.25 has been claimed as optimum for single phase-shift DFB lasers. In the practical injection current range shown in Fig. 2, the minimum linewidth for the coupled phase-shift DFB lasers would be about 0.1 MHz at a cavity length of about 1 cm. This is an order of magnitude improvement in linewidth over that of the single phase-shift DFB lasers.

In conclusion, a coupled phase-shift DFB laser structure is proposed and a simple model of it is analysed. The cavity length can be extended, without increasing the spatial hole burning effect, by this structure to achieve a narrow linewidth for coherent optical communications.

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CHARACTERISING THE UHF FACTORY RADIO CHANNEL

Indexing terms: Radio wave propagation, Mobile radio systems, Indoor radio systems, Multipath

Portable UHF factory multipath measurement apparatus is being used to measure multipath delay profiles and narrowband fading at five large manufacturing sites in the midwestern US. Preliminary data indicate that typical RMS delay spreads range from 100 to 250 ns and that average CW path loss varies as distance to the power 2.2. This work is the first report of extensive multipath measurements in factory environments.

Introduction: Futuristic flexible manufacturing facilities will probably use radio to provide portable communications and mobile robot control. In the factory environment, multipath interference caused by reflections of the transmitted signal from the surrounding building structure and inventory can cause intersymbol interference and thus limit data rates. A portable factory multipath measurement apparatus which uses both pulsed and CW transmissions has been designed for the 1100-1500 MHz band, and is being used to measure multipath delay profiles and narrowband fading in typical manufacturing facilities. Since in-depth radio propagation data for the factory environment has not previously appeared in the literature, several experiments which give insight into the communication channel are being performed. The data will be used to develop a statistical model for the factory communication channel.

Measurement apparatus: A block diagram of the multipath measurement system is shown in Fig. 1. It is similar to an apparatus recently used to measure propagation characteristics in an office building. The 1 W transmitter uses a discine antenna and may be operated in either a CW mode or in a repetitive pulsed mode. The transmitted probing signal has a 10 ns duration and a variable repetition rate from 100 to 1000 ns. The receive cart is equipped with a discine antenna mounted on an adjustable mast, a wideband low-noise amplifier, a state-of-the-art communications receiver that has been calibrated and modified to provide a direct voltage pro-
portional to the received signal envelope, a sampling oscilloscope, a square-law envelope detector and a personal computer with IEEE-488 bus.

Fig. 1 Block diagram of multipath measurement apparatus

(a) LOS (line-of-sight) path with light surrounding clutter: Such paths exist along aisles that are surrounded by relatively empty storage areas or low-density work areas (such as a machine shop) where most scatterers are lower than the height of the receiver antenna.

(b) LOS path with heavy surrounding clutter: Such paths exist along aisles in a well stocked warehouse or along aisles of an automated assembly line area, where a significant number of scatterers are located at heights greater than the receiving antenna.

(c) Obstructed path—light surrounding clutter: Such paths exist when a LOS path is blocked by inventory or machinery that is approximately the same height as the receiving antenna. Such a radio path exists across a machine shop or manual assembly area.

(d) Obstructed path—heavy surrounding clutter: Such paths exist throughout areas of the factory where the 'skyline' is busy, such as within a metal foundry or across an automated assembly line area.

Visits to several factories have indicated that there are four basic radio geographies in a typical manufacturing complex. These geographies may be classified as follows:

(a) LOS (line-of-sight) path with light surrounding clutter: Such paths exist along aisles that are surrounded by relatively empty storage areas or low-density work areas (such as a machine shop) where most scatterers are lower than the height of the receiver antenna.

(b) LOS path with heavy surrounding clutter: Such paths exist along aisles in a well stocked warehouse or along aisles of an automated assembly line area, where a significant number of scatterers are located at heights greater than the receiving antenna.

(c) Obstructed path—light surrounding clutter: Such paths exist when a LOS path is blocked by inventory or machinery that is approximately the same height as the receiving antenna. Such a radio path exists across a machine shop or manual assembly area.

(d) Obstructed path—heavy surrounding clutter: Such paths exist throughout areas of the factory where the 'skyline' is busy, such as within a metal foundry or across an automated assembly line area.

Measurements are being conducted in each of the four geographical settings at each factory. Additional data have been recorded for LOS radio paths which run parallel to walls. For all measurements, the transmitter cart is positioned in a location clear of immediate obstructions, such as in the middle of the intersection of two main aisles, within the desired geography. The receiver is moved to three locations within the geography having graduated transmitter-receiver separations (nominally 25 m, 50 m and 75 m). At each location the receiver cart is positioned for data collection in an aisle or other sensible vehicle pathway and is moved about a local (nominally 2 m square) neighbourhood. The entire data pool from the five manufacturing sites will consist of over 1200 factory multipath profiles and 35 000 received CW power measurements.

Preliminary results: First results indicate that the factory is a very slowly time-varying channel and that factory multipath spreads are similar in shape to those observed in the urban radio channel. Fig. 2 illustrates some typical observed delay
The first observable path. Fig. 2b illustrates a significant path only 6 dB weaker than the LOS path at an excess delay of 800 ns in a heavy clutter area. This reflection was deduced to be from one of the perimeter metal walls of the factory, and was the longest excess delay observed. The large excess delay of Fig. 2b results in significant multipath power arriving 50-400 ns after profiles. It is apparent that the absence of an LOS path often delays and multipath amplitudes for various factory geographies in Fig. 2 possess RMS delay spreads of several picoseconds.

The data indicate that an exponential ray-cluster channel model suggested by Saleh and Valenzuela may be valid for LOS factory radio paths. Data from severely obstructed paths, however, do not appear to fit the model. Analysis is currently being conducted to determine suitable distributions on time delays and multipath amplitudes for various factory geographies and building compositions.

Fig. 3 shows a scatter plot of signal attenuation with distance as a function of factory geography from all five of the factory sites. Each symbol on the plot represents the median signal strength for a particular location over varying antenna heights and positions. Dotted lines indicate various values of $n$, where $n$ denotes the exponential relationship of power loss with respect to distance. In many parts of the factory, the received signal power falls off at a rate less than the square of the distance due to waveguiding by the metal roofs and large metal objects which flank a typical factory aisle. Such a phenomenon has been observed in other buildings. For obstructed paths in heavy clutter, however, attenuation increases with distance to the third or fourth power.

Fig. 3 Signal attenuation against distance, from several factories

The luminescence intensity originating from semiconductors is generally very weak. The measurement of such luminescence intensities needs powerful detection and amplification systems with minimum noise generation. For the measurement of a continuous luminescence signal, the detection system consists of a lock-in amplifier with a detector. When the measurement of luminescence time constants in the hundreds of picoseconds range and below is required, the problem becomes more difficult. Real-time measurement is generally not possible because of the noise generated in resistances, large-band amplifiers and detectors. In addition, when the photodetector is fast ($\sim 100$ ps) its area is made very small ($\sim 0.2$ mm diameter), to decrease the parasitic capacitance. One method used to measure luminescence time constants with good sensitivity and whose resolution close to 10 ps is the streak camera. However, this method is very expensive and is limited to wavelengths below 1-1.5 mm. Another method is the use of an upconversion scheme (frequency addition of a photon coming from the excitation laser to a photon from the luminescence) in a nonlinear crystal such as LiLO$_3$. This second method needs careful orientation of incident optical rays to achieve phase matching of the two photons inside the crystal for obtaining a good optical conversion efficiency. The crystal and optical ray orientations for the phase matching vary with the measured wavelength. In addition, a high peak power of the excitation laser (in the kilowatt range) is needed to reach a good conversion efficiency.

In this letter we present a new technique used to measure luminescence time constants. The technique is based on previous work performed to characterise photodetector response seen using a high excitation power to work in a nonlinear regime. The incident energy and photons/pulse are about 1 J and 10$^7$, respectively. In the present study we are working in the linear regime with incident energy per pulse near $10^{-12}$ J, corresponding to about 125 incident photons/pulse on the detector for the reference beam. A block diagram of the experimental set-up is shown in Fig. 1. A 0.587 mm-wavelength laser beam of 2 ps pulse duration and 82 MHz repetition rate comes from a synchronously pumped mode-locked dye laser.