

where

$$\alpha = \sup_{0 \leq t \leq T} \left[\left(\frac{1}{p_1 - p_2} \right) \{ (-p_1 e^{-p_1 t} + p_2 e^{-p_2 t}) b k_1 + (p_1^2 e^{-p_1 t} - p_2^2 e^{-p_2 t}) \} \right] \quad (9)$$

However, this inequality implies that

$$|\dot{e}_k(t)| \leq |\alpha|^k \int_0^t \int_0^{t_1} \dots \int_0^{t_{k-1}} |\dot{e}_0(t_k)| dt_k \dots dt_2 dt_1 \quad (10)$$

and therefore that

$$|\dot{e}_k(t)| \leq |\alpha|^k \beta t^k / k! \quad (11)$$

where

$$\beta = \sup_{0 \leq t \leq T} |\dot{e}_0(t)| \quad (12)$$

Hence

$$|\dot{e}_k(t)| \rightarrow 0 \quad (13)$$

as $k \rightarrow \infty$, which implies that

$$\dot{y}_k(t) \rightarrow \dot{v}(t) \quad (14)$$

uniformly in $t \in [0, T]$ as $k \rightarrow \infty$. However, it follows from (iii) and (iv) that

$$y_k(0) = v(0) \quad (15)$$

for all $k = 0, 1, 2, \dots$. It is therefore finally evident that

$$y_k(t) \rightarrow v(t)$$

uniformly in $t \in [0, T]$ as $k \rightarrow \infty$.

Illustrative example: This theorem can be conveniently illustrated by considering the iterative learning control of the second-order plant governed by eqn. 1 with $a_1 = 2$, $a_2 = 1$ and $b = 1$, which is completely irregular and therefore cannot be controlled directly by Arimoto *et al.*² In the case $y_0(0) =$

$0 = \dot{y}_0(0)$, $v(t) = 4t^3 - 3t^4$, $u_0(t) = 0$ and $T = 1$, the rapid learning of the controller with $k_1 = 1$ and $k_2 = 1$ is shown in Fig. 1. In this case, $v(t)$ is such that $\dot{e}_k(0) = 0$ for all $k = 0, 1, 2, \dots$, and therefore no shifting of the initial velocity is required to satisfy condition (iv) of the theorem.

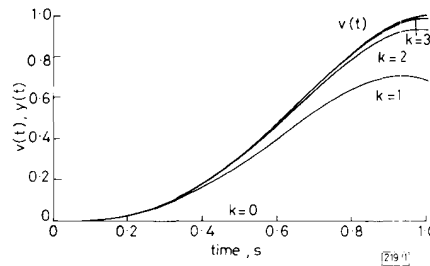


Fig. 1 Iterative learning control of second-order completely irregular plant

Conclusion: Iterative learning controllers with initial state shifting have been characterised for a class of completely irregular linear time-invariant plants. These theoretical results have been illustrated by the presentation of numerical results which demonstrate the effectiveness of the proposed iterative learning controllers for the direct control of completely irregular plants.

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DOPPLER SPREAD MEASUREMENTS OF INDOOR RADIO CHANNEL

Indexing terms: Radiowave propagation, Radiocommunication

The temporal variations caused by human movement or human-induced motion of the communication equipment, on the otherwise static indoor radio channel, are measured. For the reported narrowband measurements, a maximum Doppler spread of 6.1 Hz and a maximum RMS Doppler bandwidth of 0.87 Hz are observed.

Introduction: The path length changes in a fading multipath channel give rise to Doppler shifts, and the width of the distribution of Doppler shifts is defined as the Doppler 'spread'. The Doppler spread is the width of the received spectrum when a single tone is transmitted, and it is related to the rate at which fading occurs. The Doppler spread is important in determining the minimum signalling rate allowable for coherent demodulation and the minimum adaptation rate for an adaptive receiver.¹ For the indoor radio channel, the multipath characteristics are static at any one location until some movement occurs and causes Doppler spreading.

This letter presents calculations of RMS Doppler bandwidth and Doppler spread of the indoor radio channel caused by traffic and local movements of the communication equipment. These were controlled experiments, with the only

movement being the movement for which we were trying to determine the resulting Doppler spread. The measurements were divided into line of sight (LOS) and obstructed line of sight (OLOS).² The measurements were taken on the third floor of the three-storey Atwater Kent Laboratories at the Worcester Polytechnic Institute.

Measurements: A 910 MHz signal generated by a 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, a series of amplifiers with a gain of 60 dB, and is returned to the network analyser to determine the time variations of the channel. In a 32 s interval, the network analyser takes samples of the amplitude and phase of the received signal at the rate of 25 samples/s.

Table 1 lists the distance between the transmitter and the receiver for the 11 LOS measurements performed in the electronics laboratory. For reference purposes, measurement 1 was taken at 1 m with no movements. Three measurements at each of the three distances of 3, 6 and 12 m of receiver/transmitter separation were taken. Measurements 2, 5 and 8 were taken with people moving in the path between the transmitter and receiver. Measurements 3, 6 and 9 were taken with human traffic close to the transmitter and receiver. Measurements 4, 7 and 10 were taken with small cyclic movement of the transmitter. Measurement 11 was taken at 12 m separation with random motion of the transmitter.

For the OLOS measurements, the receiver was placed in the communication research laboratory (CRL). A total of 10 measurements, summarised in Table 1, were taken in three different transmitter locations. Location 1 was in the corridor next to the CRL; location 2 was in the microwave laboratory at the other side of the corridor; and location 3 was in the electronics laboratory next to the microwave laboratory. Measurements 1, 4 and 7 were taken with human traffic close to the transmitter. Measurements 2, 5 and 8 were taken with human traffic close to the receiver. Measurements 3, 6 and 9 were taken with small cyclic movement of the transmitter. Measurement 10 was taken at the third location with traffic in between the transmitter and receiver, but not in the same room as either the transmitter or the receiver.

Table 1 f_N AND B_D IN HZ, DISTANCE IN m AND POWER VARIATION IN dB

No.	Dis.	LOS			Dis.	OLOS		
		f_N	B_D	Power		f_N	B_D	Power
1	1	0.016	0.0	0	4	0.373	5.7	20
2	3	0.610	6.1	30	4	0.190	5.1	10
3	3	0.424	4.8	35	4	0.199	4.7	4
4	3	0.092	0.4	4	8	0.873	4.9	30
5	6	0.665	1.9	25	8	0.559	3.6	35
6	6	0.424	3.3	30	8	0.761	4.8	8
7	6	0.236	0.3	3	13	0.461	4.4	25
8	12	0.217	2.0	15	13	0.257	3.0	10
9	12	0.247	3.9	20	13	0.649	5.2	10
10	12	0.130	4.9	4	13	0.288	1.0	8
11	12	0.531	4.9	35				

Analysis of data: In the analysis of acoustic or radar signals, the maximum Doppler shift is related to the velocity of movement v_m and the transmitting frequency f_c by

$$f_d = \frac{2v_m f_c}{c} \quad (1)$$

where c is the velocity of propagation.⁵ If this equation is used as an approximation to the Doppler spread B_D of the indoor radio channel, a person walking at 3 mile/h (1.33 m/s) will produce a Doppler spread of 8 Hz for the 910 MHz transmission frequency. In the rest of this section the exact Doppler spreads of the previously described measurements are determined.

Our measurements give the response $H(f_c; t)$ of the indoor radio channel to an unmodulated sine wave of frequency $f_c = 910$ MHz. The complex autocorrelation function of $H(f_c; t)$ is $R_f(0; \Delta t)$, and the Doppler power spectrum¹ is

$$V_f(\lambda) = \int R_f(0; \Delta t) \exp(-j2\pi\lambda \Delta t) d(\Delta t) \quad (2)$$

Since $V_f(\lambda)$ is the Fourier transform of the complex autocorrelation function of $H(f_c; t)$, $V_f(\lambda) = |H(f_c; \lambda)|^2$, where

$$H(f_c; \lambda) = \int H(f_c; t) \exp(-j2\pi\lambda t) dt \quad (3)$$

The Doppler spread B_D is the range of frequencies λ over which the Doppler power spectrum $V_f(\lambda)$ is nonzero.⁴ For real measurements, $|H(f_c; \lambda)|$ is never zero, and a threshold at -40 dB is used to determine B_D . A more specific measure of the Doppler spread is the RMS Doppler bandwidth,¹ given by

$$f_N = \left[\frac{\int \lambda^2 V(\lambda) d\lambda}{\int V(\lambda) d\lambda} \right]^{1/2} \quad (4)$$

which is a measure of the distribution of the power rather than just the width of the power distribution.

Fig. 1 shows three examples of the measured $|H(f_c; t)|$ and the corresponding $|H(f_c; \lambda)|$. Fig. 1a shows LOS measurement 11 for the random motion of the transmitter. Fig. 1b

shows OLOS measurement 1 with human traffic close to the transmitter. Fig. 1c shows OLOS measurement 9 for cyclic motion of the transmitter. Table 1 gives both B_D and f_N for all the measurements. Except for LOS measurement 1, which was taken with no movement, the f_N fall in the range 0.1–0.9 Hz and the B_D are less than 6.1 Hz. The cyclic motion of the transmitter caused power variations of less than 10 dB, and movement of people caused power variations of up to 35 dB for both LOS and OLOS measurements.

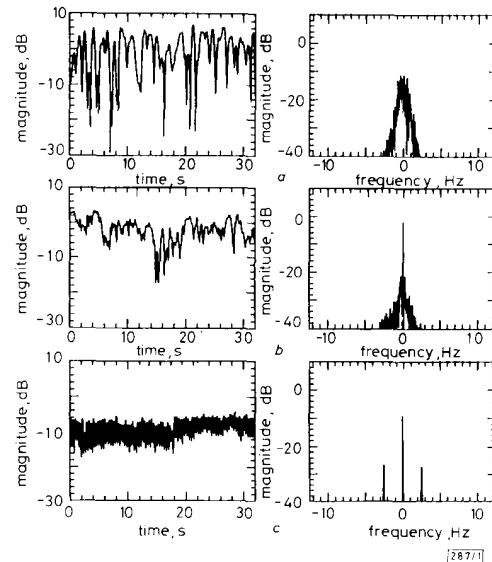


Fig. 1 Three examples of measured $|H(f_c; t)|$ and corresponding $|H(f_c; \lambda)|$
a LOS, 11 b OLOS, 1 c OLOS, 9

Using the method described in Reference 6, log-normal, Weibull and Rayleigh distributions are examined as possible fits to the measurement data. The Rayleigh distribution provides a close fit for all measurements except for those with power fluctuations of less than 10 dB. In wideband measurements, the power fluctuations are always small, and the Rayleigh distribution is never a close fit.³

Conclusions: Doppler spreads in the range 0.3–6.1 Hz and RMS Doppler bandwidths in the range 0.1–0.9 Hz were measured for typical movement in the indoor radio channel. For envelope fading variations of less than 10 dB, the Rayleigh distribution provided a poor fit to the data.

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GaAs W-BAND IMPATT DIODES FOR VERY LOW-NOISE OSCILLATORS

Indexing terms: Semiconductor devices and materials, GaAs, Impatts, Microwave oscillators

W-band single-drift flat-profile impatt diodes were fabricated from GaAs MBE material and tested in a full-height waveguide resonant cavity with resonant cap. A quasi-optical parabolic Fabry-Perot resonator was used to determine the FM noise of the GaAs impatt oscillator. With a minimum noise measure of 20 dB at power levels around 20 mW, impatt diode oscillators can compete well with oscillators using Gunn devices. The $(N/C)_{FM} = -82$ dBc measured at 100 kHz frequency off-carrier and at $Q_{ex} = 95$ is comparable to the value obtained from Gunn devices. The maximum available output power of 270 mW, however, markedly exceeds that of Gunn oscillators.

Introduction: It has recently been shown¹ that single-drift flat-profile GaAs impatt diodes successfully operate up to W-band frequencies with sufficiently high output power (270 mW typically) and efficiency (6% typically). These diodes on diamond heat-sinks are fabricated from MBE material using a selective etching technology² to achieve reproducible results. In this letter results of the first noise measurements on W-band GaAs impatt diodes are reported. The details of device structure and growth procedure are given elsewhere.¹ All diodes are tested in a full-height waveguide resonant cavity with resonant cap on the diode as previously described in Reference 3.

Measurement set-up: The complete measurement set-up is depicted in Fig. 1. As a versatile tool to convert the FM into AM, a quasi-optical parabolic Fabry-Perot resonator is used. This resonator is similar to the system described in References 4 and 5 for W-band and D-band applications. A detector at the output of the resonator delivers the demodulated FM signal. The low-noise amplifier decouples the signal of the detector output from the cable capacitance and the load of the selective level meter, thereby increasing bandwidth and signal level. The bias network included in the amplifier provides a constant current of $I_b \approx 10 \mu A$ through the detector diode,

and improves the sensitivity of the detector in the same way as discussed in Reference 5.

The tracking generator of the selective level meter is used to determine the sensitivity of the Fabry-Perot resonator with a standard Bessel zero method at the test signal frequency f_i . The sensitivity $S = u_i \sqrt{(2)/(2 \cdot 405 f_i)}$ for a demodulated signal u_i at the detector lies between 3 and 15 nV/Hz, depending on the input power. The frequency and amplitude of the modulating Bessel zero signals are kept constant during one computer-aided measurement cycle. This signal is switched to the diode between each measuring point, where the offset frequency f_m changes. Using this signal, both a small drift in the modulation index of the impatt oscillator can be seen or the spectrum analyser and, more importantly, a drift in the sensitivity of the quasi-optical resonator (caused by mechanical drift or drift of the oscillator frequency) can be taken into account by the computer program. Additional errors thus caused by drift effects can be excluded within the run, i.e. for all the noise levels at frequencies off-carrier between 2 kHz and 1.7 MHz.

The external quality factor Q_{ex} of the impatt oscillator is determined by the self-injection locking method, for which the first 20 dB coupler in Fig. 1 with the attenuator and a tunable short is used.

Results: Fig. 2 shows the typical FM noise deviation Δf_{rms} for two different diodes and power levels plotted as a function of the frequency f_m off-carrier. In both cases a clear decrease proportional to $f_m^{-1/2}$ is found up to an offset frequency f_m of about 100 kHz. Above this flicker noise corner frequency, Δf_{rms} remains constant at 10 Hz/ $\sqrt{(\text{Hz})}$ at $P_0 = 22.5$ mW ($Q_{ex} = 95$), and 15 Hz/ $\sqrt{(\text{Hz})}$ at $P_0 = 9.8$ mW ($Q_{ex} = 80$).

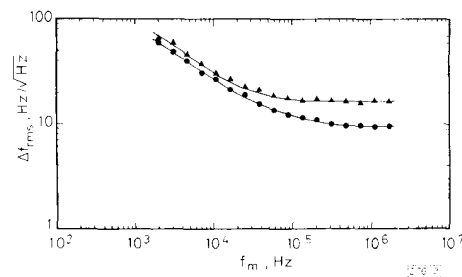


Fig. 2 FM noise deviation Δf_{rms} of typical GaAs single-drift flat-profile impatt diodes against frequency off-carrier f_m

- $f_0 = 94.5$ GHz, $P = 22.5$ mW, $Q_{ex} = 95$
- ▲ $f_0 = 89.9$ GHz, $P = 9.8$ mW, $Q_{ex} = 80$

The single-sideband FM noise/carrier ratio $(N/C)_{FM}$ at a frequency off-carrier f_m can be calculated from the FM fre-

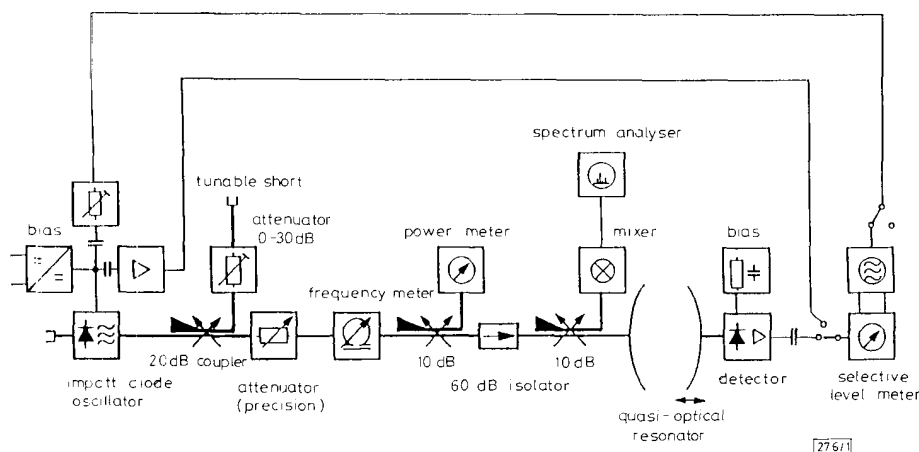


Fig. 1 Block diagram of noise measurement set-up with quasi-optical resonator