

Comparative signal-to-noise analysis of fibre-optic based OCT systems.

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Abstract

Several optical coherence tomography (OCT) systems are proposed using optical-fibre components and based around Fizeau sensing interferometers. The theoretical signal-to-noise ratio (SNR) is calculated for each of the proposed configurations, using a constant set of assumed values for illumination and detection parameters. The SNR values obtained are compared with values calculated for typical existing configurations based around Michelson interferometers.

Fizeau-based systems incorporating a secondary processing interferometer offer the advantage over current interferometer configurations of down-lead insensitivity, which prevents signal fading and reduces thermal fringe drift. The most basic form of the Fizeau system makes inefficient use of optical power, and has a low SNR compared with the widely used Michelson configuration. However, the results of the analysis described in this paper show that the SNR for more sophisticated Fizeau configurations, incorporating optical circulators and balanced detection systems, can be as high as the value for the most sensitive existing fibre-based OCT systems. Fizeau configurations therefore offer the combined advantages of optimised SNR and down-lead insensitivity, indicating their suitability for use in relatively poorly-controlled environments such as *in-vivo* measurements.

1. Introduction

Optical coherence tomography (OCT) is a low-coherence scanning technique used to determine the sub-surface refractive-index structure of transparent [1],[2] or turbid [3],[4] materials with a resolution, dependent upon source coherence length, of between about 1 and a few tens of μm [5],[6]. In biological tissue samples the penetration depth of the illuminating radiation is typically 1-2 mm [7], and the technique is therefore of interest in studying changes in surface tissue layers, e.g identification of pre-cancerous changes in the tissue layers of the skin [8] or oesophagus [9].

[insert figure 1 about here]

The most widely used configuration for fibre-optic based OCT is a Michelson interferometer formed from a directional coupler (figure 1), in which either an external mirror or the polished (and sometimes coated) end of one coupler output fibre generates the reference reflection [10],[11]. This is mixed, using appropriate lenses at the fibre output, with light backscattered from a sample positioned close to the other coupler output arm. The path length difference between the interferometer arms is scanned linearly with time.

When a source of low temporal coherence is used to illuminate the system, interference fringes are observed only when the path length difference at any point in time is less than the coherence length of the source. Thus a plot of the variation in fringe magnitude seen during a scan represents the variation of the backscattered signal from different depths within the sample. The spatial resolution perpendicular to the sample surface is of the order of the coherence length. A single scan produces a one-dimensional map of

refractive-index variation as a function of sample depth. By repeating the depth scan over a grid of positions on the sample surface, a two- or three-dimensional map of subsurface structure is obtained [12]. Various types of rapid scanning techniques have been investigated to reduce the time taken for acquisition of a three-dimensional image [13],[14].

The Michelson arrangement for OCT is widely used. Other configurations based on Mach-Zehnder interferometers have been suggested, all resulting in very similar values of SNR to the Michelson configuration, when used with balanced detection [15]. However, both the Michelson and Mach-Zehnder configurations have disadvantages. The signal and reference beams travel in different arms of the directional coupler. They therefore experience differential polarisation state changes as a result of physical perturbation of the fibre introducing birefringence, and differential phase changes caused by variations in ambient temperature around the fibre arms. Periodic fading or loss of the interference signal is experienced if the states of polarisation are mismatched in the region where interference occurs [16]. Under laboratory conditions, such changes are typically slow and can be reduced by the inclusion of polarisation-state controllers in the system [17], although regular adjustment of the relative polarisation states is likely to be necessary.

When an OCT system is required to make clinical measurements including internal investigations, control over ambient conditions is much more difficult and polarisation mismatches can become more troublesome. Several approaches to reducing the problem are possible: it is possible under favourable circumstances simply to make measurements only when the polarisation states are well matched. However, this can lead to

measurement artefacts being missed if ambient conditions change significantly during the course of a measurement.

Another alternative is to construct the interferometer using polarisation-preserving fibres and fibre components [18]. This is a satisfactory solution when the sample is non-birefringent. For linearly polarised light, coupled into an eigenmode of the interferometer fibre, the state of polarisation (SOP) is preserved throughout. However, if the sample itself causes depolarisation, then the SOP of the backscattered light will no longer be preserved within the fibres and, once again, signal fading will occur.

A more robust solution, and the one proposed in this paper, is to employ a completely different interferometer configuration, which is insensitive to changes in ambient conditions. A Fizeau-based configuration [19] is considered here which, in its most basic form, makes use of a single arm of the same type of directional coupler used for the Michelson system. The sample is now positioned close to the output arm and, again using appropriate optics, light is focused into the sample and the backscattered light is recoupled into the illuminating fibre. The reference beam, however, is now formed from the reflection at the glass/air interface corresponding to the termination of the distal end *of the same* fibre arm, in a Fizeau interferometer arrangement (figure 2).

[insert figure 2 about here]

The advantage of this system is that, apart from the section of path length within the sample itself, the interferometer, which is formed between the fibre end and the sample, is entirely free-space. The delivery fibre provides a common path for the reference and signal beams, so that any polarisation changes that occur are the same for both interfering

beams. This gives the system immunity to polarisation variation caused by ambient changes, and is known as ‘down-lead insensitivity’.

For a birefringent sample, variations in signal intensity will occur, but these are now a function only of the sample birefringence, and are no longer connected with random polarisation drifting in the fibres as in the Michelson configuration. They can be made use of to extract information about the magnitude and orientation of sample birefringence [20].

The basic form of the Fizeau-based OCT system shown in figure 2 makes poor use of the available light; it can be seen from the figure that 75% of the power from the source is lost in the system. This configuration also suffers from the severe drawback that the maximum theoretical signal-to-noise ratio for a given source and detector is much lower than that for the Michelson-based system [21]. This may be the reason why Fizeau-based OCT has not previously been investigated. However, as discussed below, the use of optical circulators and novel processing configurations can restore the theoretical SNR to a value comparable with that for the Michelson configuration, with the added advantage of down-lead insensitive operation.

2. Theory of signal-to-noise-ratio calculation

The received optical power in an OCT system is usually low. Broadband, infra-red solid-state sources are generally used because they allow good tissue penetration and depth resolution. However, the output powers available from these devices are typically no more than a few tens of milliwatts, and reflectivity values at tissue interfaces are small. Thus optical power levels at the detector fall typically in the nanowatt to microwatt range.

Ideally, systems are operated at high bandwidth to enable fast scanning and rapid acquisition of images. The combination of low power and high bandwidth means that the signal-to-noise ratio (SNR) in OCT is likely to be relatively low for standard detection techniques, and that careful consideration will have to be given to system design. The value of SNR must exceed that required to resolve the small refractive index variations (around 0.01-0.1) typical of biological tissue [22] .

The maximum SNR of an OCT system [15] is defined as the ratio of the mean square signal photocurrent $\langle I_s^2 \rangle$ from the detector, under path-matched conditions, to the total photocurrent variance σ_i^2 . The SNR calculations in section 3 make use of the optical power P_r in the reference beam, power P_s in the sample beam and the optical power P_x of stray incoherent light at the detector. Corresponding power reflectivities R_r , R_s and R_x are also used and the responsivity ρ of the detector is required. For maximum fringe visibility, the states of polarisation of interfering beams must be identical, or reductions in SNR will occur. This paper assumes unpolarised light from the source. Although this is not always the case experimentally, it is a valid assumption for the purpose of comparing the maximum expected SNR for a range of proposed interferometer configurations.

The mean square signal photocurrent is a function of the optical powers in the reference and signal beams and of the detector responsivity.

There are three sources of noise to be considered in calculating the SNR of any OCT system. The first is receiver noise, which arises due to the random thermal motion of electrons within the detection/amplification components. For commercial photodetectors, the receiver noise is usually specified by the manufacturer.

The two other sources of noise are both dependent upon the average photocurrent I_{dc} at the detector or, in the case of balanced detection, detectors. Shot noise arises as a result of the random distribution in arrival times of photons at the detector from a monochromatic light source. The shot noise photocurrent variance σ_{sh}^2 that results from this Poisson process is given by

$$\sigma_{sh}^2 = 2qI_{dc}B, \quad (1)$$

where q is the electronic charge and B the detection bandwidth [23] .

The final source of noise to be considered is excess photon noise, which arises due to the random arrival of photons from a broad band light source. This is a Bose-Einstein process, with different statistics from shot noise, and the photocurrent variance for the excess noise [24] is given by

$$\sigma_{ex}^2 = I_{dc}^2 B / \Delta \nu . \quad (2)$$

Here, $\Delta \nu$ is the frequency linewidth of the source.

When a balanced receiver can be used, much of the excess noise has identical time dependence in both detectors, and is therefore cancelled. The dominant remaining noise contribution at moderate optical powers is often shot noise, and the resulting improvement in SNR can be as much as 40 dB. However, in some configurations there can be a phase difference between the beams arriving at the two detectors for stray, incoherent beams arising from unwanted reflections [25]. In this situation, the beating that occurs between non-coherent spectral components of the broadband source gives rise to a form of noise called beat noise. The beat noise is given by

$$\sigma_{be}^2 = \rho^2 P_x P_r B / \Delta \nu . \quad (3)$$

3. Calculated SNR for selected OCT configurations

The SNR $\langle I_s^2 \rangle / \sigma_i^2$ is calculated for selected optical fibre OCT configurations, using a constant set of assumed values for the required parameters as follows: $R_x = 0.0005$, $R_r = 0.1$, $\rho = 0.95$ A/W, receiver noise = 2pA/ $\sqrt{\text{Hz}}$, source power $P_0 = 20$ mW, wavelength $\lambda = 1300$ nm and source bandwidth = 50 nm. The electrical bandwidth, $B = 1$ MHz. These parameters have been selected to be identical to those chosen by Rollins and Izatt [15], to allow comparison with the SNR analysis they use for their interferometer configurations. However, in calculating the average photocurrent, Rollins and Izatt assume the power backscattered from the sample P_s to be negligible compared with the reference power, even though the sample reflectivity of $R_s = 1$ is an order of magnitude higher than the reference reflectivity of $R_r = 0.1$. The additional term makes a significant contribution in the calculations of shot noise and excess noise. We assert, therefore, that it should be included, and we therefore obtain lower theoretical values of SNR than Rollins and Izatt for the same configurations. However, the general conclusions about the benefits of balanced detection are unaffected, as can be seen from the analysis below.

In each case, we calculate the SNR under the assumption $R_s = 1$, which corresponds to a 100% mirror as the sample. This is not intended to represent a realistic biological sample reflectivity, but gives a basis for comparison of the various configurations. For completeness, the SNR is also calculated in each case using a more realistic sample reflectivity value. As an example, values of relative permittivity have been published for bovine bronchus tissue, giving 1.96 for the submucosa and 2.1025 for the epithelium at 1550 nm [22], leading to a reflectivity of 0.00031 [19]. For simplicity, a value of $R_s = 0.001$ is used here in the sample calculations. The reference reflectivity of $R_r = 0.1$,

chosen to match that in the set of parameters used by Rollins and Izatt, is higher than the value of 0.04 expected for the glass/air interface at a cleaved fibre end. However, it is possible to obtain values of reflectivity up to about 0.3 at a fibre end by the application of a titanium dioxide coating to the cleaved face [26], so the value of $R_r = 0.1$ used is readily achievable.

3.1 Michelson interferometer with a single detector

The most widely used optical-fibre configuration for OCT measurements is still the Michelson interferometer. The sample is positioned at the output of one interferometer path, and the reference surface at the output of the other. Consider first a system using a single detector, as shown in figure 1. The calculation here assumes that the splitting element is a directional coupler with a split ratio of α . Ignoring losses in the system, the powers received at the detector from the sample arm, reference arm and unwanted reflections respectively are:

$$P_s = (P_0 \alpha R_s (1 - \alpha))(1 - R_x)^2, \quad (4a)$$

$$P_r = (P_0 (1 - \alpha) R_r \alpha), \quad (4b)$$

$$P_x = P_0 \alpha R_x (1 - \alpha). \quad (4c)$$

The interference term produces a periodic signal photocurrent I_s , which varies cosinusoidally as the interferometer phase θ is scanned linearly.

$$I_s = 2\rho \left[P_0^2 \alpha^2 (1 - \alpha)^2 R_r R_s (1 - R_x)^2 \right]^{1/2} \cos \theta, \quad (5)$$

and the average photocurrent is given by I_{dc} , where

$$\begin{aligned}
I_{dc} &= \rho(P_r + P_s + P_x) \\
&= \rho(P_0\alpha(1-\alpha))[(R_s(1-R_x)^2 + R_r + R_x)].
\end{aligned} \tag{6}$$

Calculating the shot noise and excess noise from these expressions, a value of SNR is obtained which turns out to be almost independent of the split ratio α over a very wide range, for values of α between about 0.05-0.95. A graphical representation of the results is shown by line (a) in figure 3(i). The maximum SNR is obtained for $\alpha=0.5$. This is a typical result; it turns out that for all configurations examined below, the optimum split ratio is 0.5 and there is generally a rather weak dependence of SNR on the split ratio.

[insert figure 3 about here]

A graph of the SNR as a function of R_s for this configuration is shown as line (a) in figure 3(ii). Assuming $R_s = 1$ results in a SNR of 62 dB, while assuming $R_s = 0.001$ gives a reduced SNR of 52 dB. A maximum value of 67 dB occurs for a sample reflectivity of 0.1. This is to be expected intuitively since the reference and signal intensities are matched at this value, and all signal light contributes to the generation of interference fringes.

3.2 Michelson interferometer with balanced detection

Consider now the modified configuration shown in figure 4, with an optical circulator included to allow balanced detection [15]. This is a process whereby the signals from two matched detectors, positioned to monitor both outputs of the Michelson interferometer, are subtracted; a scheme which doubles the magnitude of the interference signal while suppressing much of the noise.

[insert figure 4 about here]

The use of balanced detection in this configuration has three important effects:

- (a) The magnitude of $\langle I_s^2 \rangle$ increases by a factor of 4.
- (b) The total noise variance is doubled, as the noise appears on each of the two detectors.
- (c) The excess noise is cancelled, though this term must be replaced in the calculations by the beat noise term, which corresponds to the component of excess noise not removed by the balanced detector.

When these modifications are introduced, the calculated values of SNR increase significantly, as shown by lines (b) in figures 3(i) and 3(ii). This is largely due to the cancellation of the excess noise. Shot noise now makes the dominant contribution to the overall noise variance, although the beat noise component also becomes more important for values of R_s lower than about 0.01.

There is some dependence of SNR upon the chosen value of α in this configuration, through the beat noise term, and a maximum value of 94dB is obtained for $R_s = 1$, at $\alpha = 0.5$. The SNR remains above 90dB for values of α between 0.1 and 0.9.

When the lower value of $R_s = 0.001$ is taken, a maximum SNR of 73 dB is obtained, again for $\alpha = 0.5$. Varying the reference reflectivity now has little effect; the balanced detection arrangement reduces the sensitivity of the system to differences between signal and reference power.

3.3 Fizeau configuration using directional coupler, with Michelson processing interferometer and a single detector

The simplest form of Fizeau-based OCT system, shown in figure 2, uses a single directional coupler [9],[21] . In this arrangement, there is no advantage in a variable

splitting ratio, so we assume a 50/50 split ratio. Calculation of the interference term is now more complicated, as interference can only occur between beams that are path-matched (to within the source coherence length) after their passage through both Fizeau and processing interferometers.

Assuming a lossless 50/50 beam splitter in the Michelson interferometer, we denote the longer beam path in the Michelson by the suffix *a*, and the shorter path by the suffix *b*.

The powers at the detector are then given by the equations:

$$P_{sa} = P_{sb} = (P_0(1 - R_r)R_s)/16, \quad (7a)$$

$$P_{ra} = P_{rb} = (P_0R_r)/16. \quad (7b)$$

Only two of these four components, P_{sb} and P_{ra} , are path-matched at the detector, therefore the interference term is given by

$$I_s = 2\rho[P_{sb}P_{ra}]^{1/2} \cos \theta = \frac{2\rho}{16} [P_0^2 R_s R_r (1 - R_r)]^{1/2} \cos \theta. \quad (8)$$

The average photocurrent is

$$I_{dc} = \rho\left(\frac{P_0}{8}\right)[(R_s(1 - R_r)^2 + R_r)]. \quad (9)$$

Calculation of the SNR for this configuration leads to values of 56 dB when $R_s = 1$ and 46 dB when $R_s = 0.001$. The dependence of SNR on R_s is very similar to the single-detector Michelson case, as seen from the graph in figure 5(a). Calculated SNR values are about 6 dB lower than the values obtained for the single-detector Michelson configuration. The signal reflectivity for which the maximum SNR is obtained will depend on the conditions assumed. In this case, the maximum SNR of 61 dB is obtained when $R_s = 0.1$.

[insert figure 5 about here]

3.4 Fizeau configuration using optical circulator, with Michelson processing interferometer and a single detector

This is very similar to case 3.3 above, the only difference being improved use of optical power. The use of an optical circulator, as shown in figure 6, allows all the light from the source to be transmitted to the sample and all backscattered light from the sample to be transmitted to the processing interferometer.

[insert figure 6 about here]

If losses in the circulator are ignored, then:

$$I_s = 2\rho[P_{sb}P_{ra}]^{1/2} \cos \theta = 2\rho \left[\frac{P_0^2 R_s R_r (1 - R_r)}{16} \right]^{1/2} \cos \theta, \quad (10)$$

$$I_{dc} = \rho \left(\frac{P_0}{2} \right) [R_s (1 - R_r)^2 + R_r] \quad (11)$$

and the SNR values are unchanged from case 3.3 since the dominant excess noise term is proportional to the mean square signal. Line (a) in figure 5 therefore again represents the variation of SNR for this configuration. Varying the split ratio of the beam splitter in the receiving interferometer of this configuration has an insignificant effect upon the values of SNR obtained.

3.5 Fizeau configuration using a 4-port optical circulator, with Michelson processing interferometer and balanced detection

As with the Michelson configuration, the use of balanced detection in this configuration, shown in figure 7, has three main effects:

- (a) The magnitude of $\langle I_s^2 \rangle$ increases by a factor of 4.
- (b) The total noise variance is doubled, as the noise appears on each of the two detectors.
- (c) The excess noise is cancelled. Although the contribution of any remaining beat noise to the total photocurrent variance must be considered, there are in this configuration no fibre ends within the Michelson processing interferometer to give rise to significant spurious reflections. The fibre end reflection within the Fizeau interferometer is in this case used as the system reference beam and therefore no longer contributes as a source of unwanted noise.

[insert figure 7 about here]

If we can simply set the beat noise term to zero, the SNR is very straightforward to calculate, resulting in values of 94 dB for $R_s=1$ and 74 dB for $R_s=0.001$. The form of the SNR dependence on R_s , shown as line (b) in figure 5, is now identical to that for the balanced Michelson configuration. The maximum SNR is obtained when $R_s=1$, and declines rapidly when this reflectivity falls below 0.1. These values demonstrate that the inclusion of an optical circulator and balanced detection in the system design raise the maximum theoretical SNR of the Fizeau-based OCT system to a level identical to that for the more widely used Michelson configuration.

In practice, the configuration of figure 7 is not easy to align. Because both beams from the interferometer must be re-coupled into the fibre output port of the circulator, there tends to be a large loss factor at this point in the system, which degrades the SNR

severely. The substitution of a Mach-Zehnder processing interferometer, as discussed in the set of configurations below, eases the practical alignment problem and provides immediate access to the complementary interferometer outputs for balanced detection.

3.6 Fizeau configuration using optical circulator, with Mach-Zehnder processing interferometer and single detector

The SNR is calculated for both single- and balanced-detection versions of the system shown in figure 8, using paired mirrors at 90° as the scanning element in the processing interferometer. A single scanning mirror normal to the beam direction, together with a bulk-optic circulator at this corner of the Mach-Zehnder interferometer could replace the mirror pair.

[insert figure 8 about here]

If the split ratio of the first beamsplitter in the system is $\alpha/(1-\alpha)$ and the two possible beam paths through the Mach Zehnder are denoted by the suffices 1 and 2, we obtain four expressions for optical power at the detector.

For a single detector:

$$P_{s1} = (P_0(1 - R_r)R_s)\alpha / 2, \quad (12a)$$

$$P_{s2} = (P_0(1 - R_r)R_s)(1 - \alpha) / 2, \quad (12b)$$

$$P_{r1} = P_0 R_r \alpha / 2, \quad (12c)$$

$$P_{r2} = P_0 R_r (1 - \alpha) / 2. \quad (12d)$$

The interference term and dc photocurrent are, respectively,

$$I_s = 2\rho[P_{s1}P_{r2}]^{1/2} \cos \theta = 2\rho \left[\frac{P_0^2 R_r R_s (1 - R_r) \alpha (1 - \alpha)}{4} \right]^{1/2} \cos \theta, \quad (13)$$

$$I_{dc} = \rho \left(\frac{P_0}{2} \right) [(R_s(1 - R_r) + R_r)]. \quad (14)$$

The calculated SNR in this situation (figure 5(a)) is identical to that for the comparable idealised Michelson processing system, at 56 dB when $R_s=1$ and 46 dB when $R_s=0.001$, with a maximum value of SNR=60 dB when $R_s=0.1$. There is a slight falling off of the SNR for an asymmetric split ratio of the beam splitter, but for α between 0.1 and 0.9, the value does not fall by more than 4 dB.

With balanced detection, the usual differences in the terms are seen, and the SNR values are much higher, at 94 dB for $R_s=1$ and 74 dB for $R_s=0.001$. Once again, these are identical to the values obtained using a Michelson processing interferometer (figure 5(b)). As for the single detector, a slight falloff in SNR occurs if the beamsplitter has an asymmetric splitting ratio.

The calculated SNR values for all the above configurations are collected together in table 1, for ease of comparison.

[insert table 1 about here]

From inspection of the table, it is clear that the theoretical SNR of the ideal standard Michelson and Fizeau configurations, using balanced detection, turns out to be identical. The practical difficulties associated with constructing the Fizeau/Michelson combination are, however, likely to reduce the experimental value found for this configuration significantly.

4. Discussion

The theoretical SNR values for the basic forms of both Michelson- and Fizeau-based OCT systems, using a directional coupler and a single detector, are similar, though the value for the Michelson-based system is slightly higher. The experimental difficulty in recoupling beams from the processing interferometer into fibre for the Fizeau configuration tends to reduce the SNR still further in practice, and the Michelson configuration is therefore to be preferred when polarisation problems are not severe.

It is interesting that the use of a circulator alone does not, for moderate source power, improve the SNR of the Fizeau configuration, since the mean square signal photocurrent and the noise variance are approximately proportional. For very low source powers it is likely that the use of the circulator would result in some improvement.

In both cases, the use of balanced detection (with, in the Fizeau configuration, an optical circulator), results in an increase of 30-40 dB in the expected SNR. However, the experimental problem with the Fizeau configuration persists, and the calculated SNR is likely to be an overestimate in this case.

The use of a Mach-Zehnder processing interferometer in the Fizeau configuration greatly eases alignment. The two complementary outputs are automatically available from this type of interferometer, facilitating the use of balanced detection and avoiding the requirement to recouple from the interferometer into fibre. The theoretical SNR for this configuration is in fact identical to that for the Michelson configuration with balanced detection, at 94 dB for $R_s=1$ and 74 dB for $R_s=0.001$. Since alignment of the Fizeau/Mach-Zehnder configuration is relatively straightforward, we suggest that the additional advantage of down-lead insensitivity obtained with this version of the Fizeau

OCT system makes it a good candidate for measurements when polarisation variation might otherwise be a problem.

5. Conclusions

A number of optical-fibre Fizeau-based OCT configurations have been proposed and the theoretical maximum SNR value for each configuration has been calculated under a standard set of assumed illumination and detection conditions. Comparison of the various designs shows that, although the basic Fizeau OCT system has poor SNR compared with the more usual Michelson configuration, the use of optical circulators and balanced detection can ensure an SNR comparable with that of the corresponding Michelson interferometer.

The possibility of constructing a Fizeau-based system with good SNR is relevant in clinical OCT, since this configuration offers the advantage of down-lead sensitivity, giving it immunity to environmental perturbations, which are likely to occur during *in-vivo* measurements. The widely used Michelson configuration, conversely, can suffer from polarisation-induced signal fading under similar conditions.

The Fizeau configurations outlined above use relatively slow mechanical scanning of a mirror to vary the optical path difference. However, it would be possible in any of the systems shown to replace the scanning mirror with a fast-scan element e.g. a grating-based phase control delay line [14].

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Figure Captions

Figure 1. Michelson interferometer using an unbalanced directional coupler. BBS=broadband source, $\alpha/(1-\alpha)$ = coupler splitting ratio.

Figure 2. Fizeau/Michelson combination using a 50/50 coupler. BBS=broadband source, IML=index matching liquid, BS=beam splitter.

Figure 3. SNR for Michelson configuration OCT systems as a function of (i) coupler split ratio ($R_s=1$) and (ii) signal beam reflectivity ($\alpha=0.5$) with (a) single detector, (b) balanced detection in each case.

Figure 4. Michelson interferometer using directional coupler, 3-port circulator and balanced detection.

Figure 5. SNR for Fizeau/Michelson and Fizeau/Mach-Zehnder configuration OCT systems as a function of signal beam reflectivity using (a) single detector, (b) balanced detection.

Figure 6. Fizeau/Michelson combination using a 3-port circulator.

Figure 7. Fizeau/Michelson combination using a 4-port circulator and balanced detection.

Figure 8. Fizeau/Mach-Zehnder combination using a 3-port circulator with (a) a single detector, (b) balanced detection.

Table 1. Comparison of calculated SNR values for the OCT configurations of sections (i)-(iv).

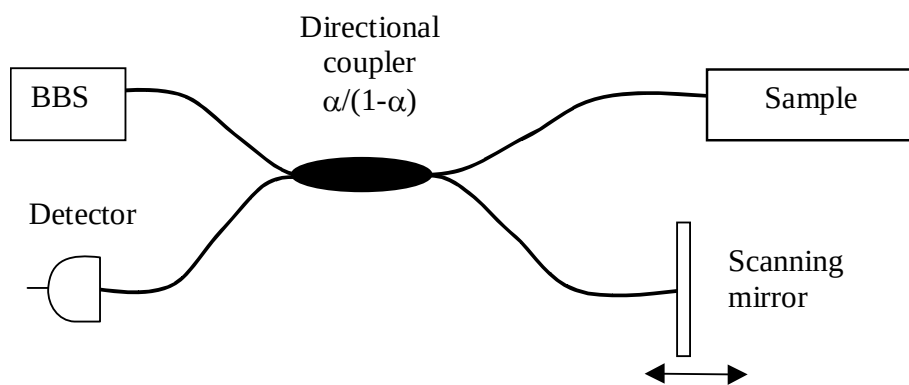


Figure 1.

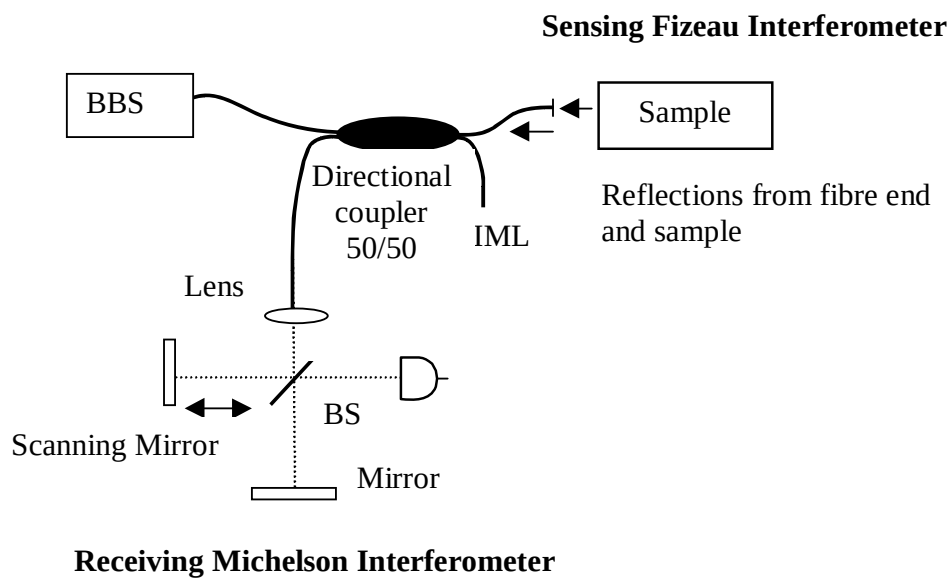
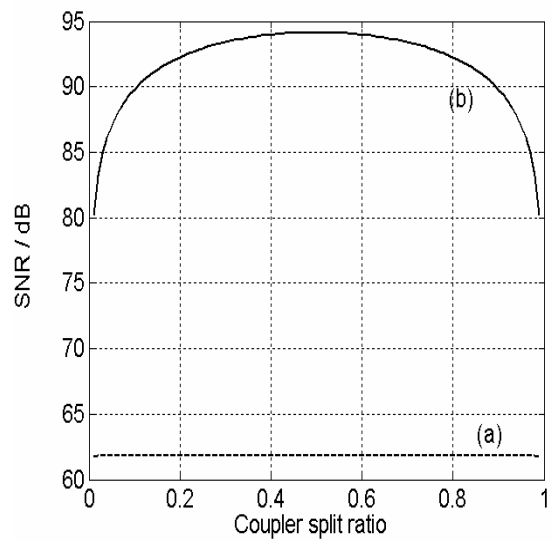


Figure 2.



(i)

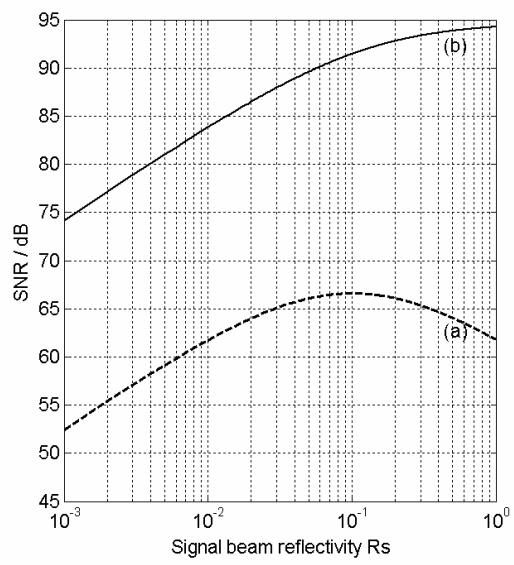


Figure 3.

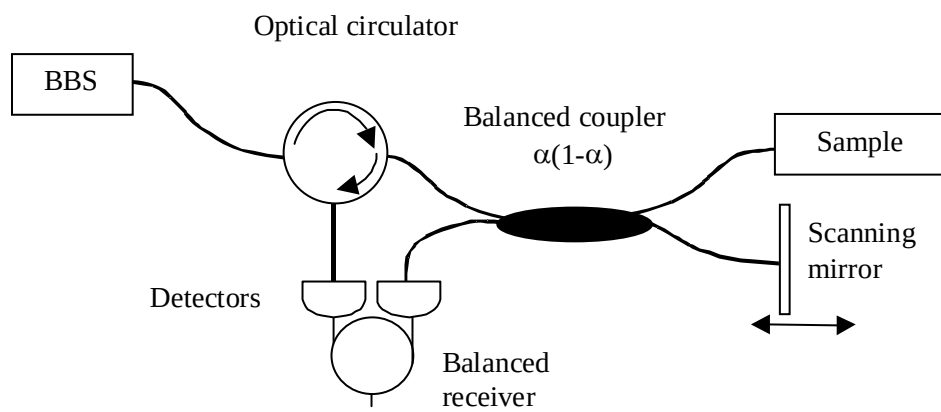


Figure 4.

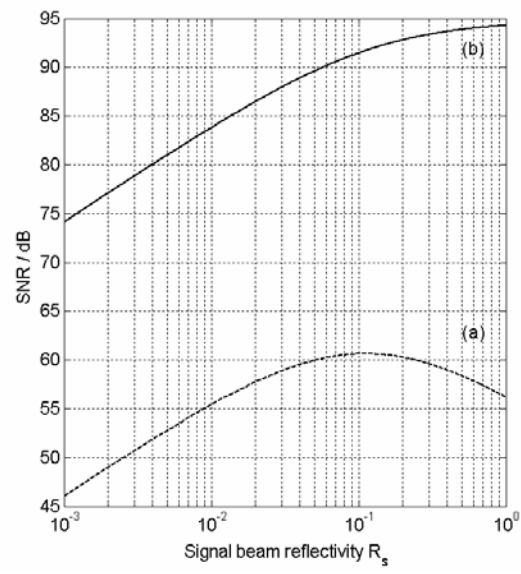


Figure 5.

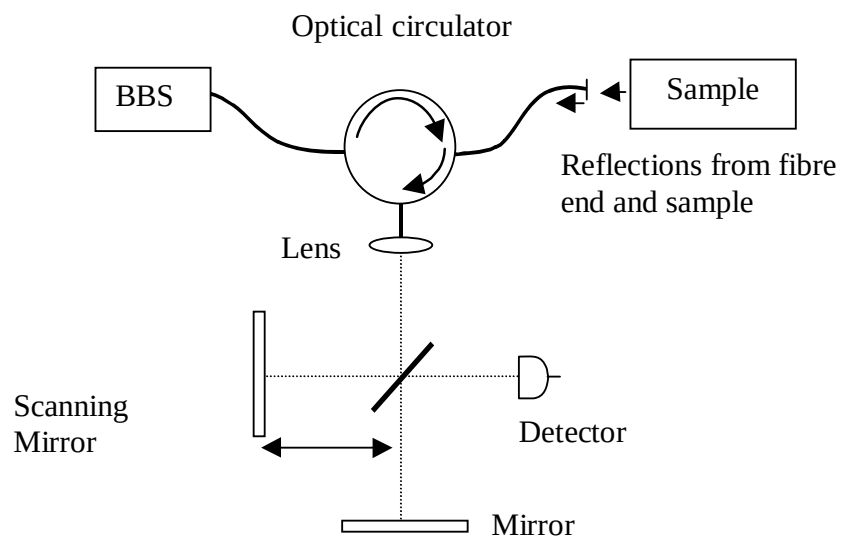


Figure 6.

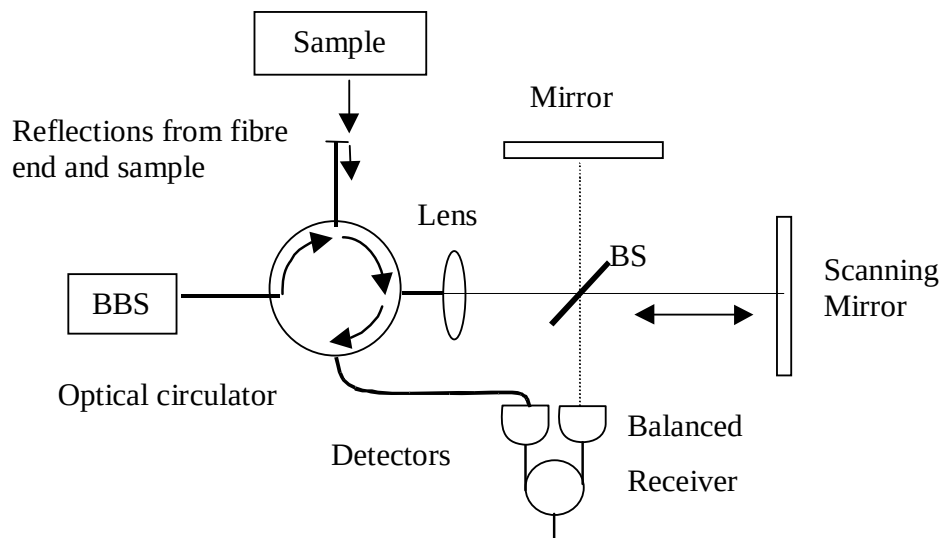


Figure 7.

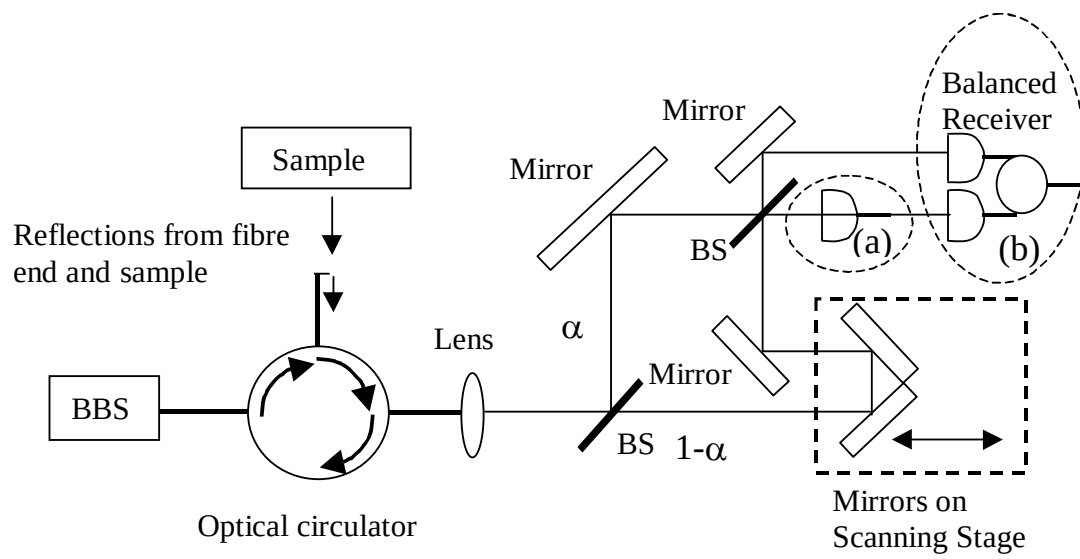
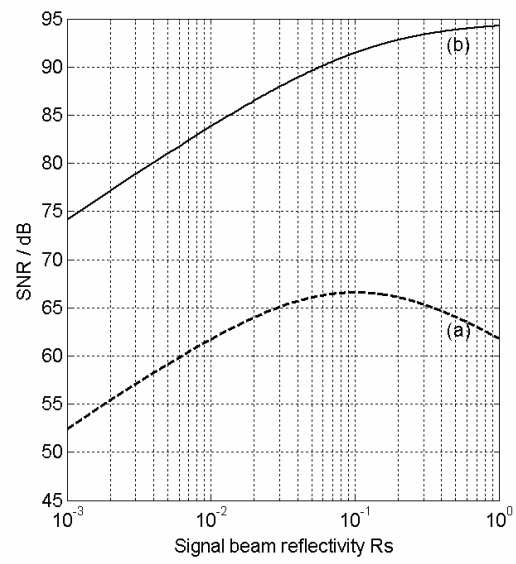


Figure 8.

OCT configuration	SNR /dB	SNR /dB
	$R_s=1$	$R_s=0.001$
Standard Michelson (unbalanced coupler)– single detector	62	52
Michelson with circulator and balanced detection	94	73
Fizeau/Michelson combination (50/50 coupler or circulator) – single detector	56	46
Fizeau/Michelson with circulator and balanced detection	94	74
Fizeau/Mach-Zehnder combination with circulator – single detector	56	46
Fizeau/Mach-Zehnder combination with circulator and balanced detection	94	74

Table 1.





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Comparative signal-to-noise analysis of fibre-optic based optical coherence tomography systems

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