Novel passive fibre-cavity design for ring-down experiments using a multimode optical waveguide

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ABSTRACT

A novel fibre-cavity design based on highly reflective gold coatings, vapor-deposited to the two end faces of a 400\,\mu m multimode waveguide, is presented. In contrast to common fibre-cavity approaches, the laser pulses are not coupled through the reflective coatings into the cavity but through a micro hole in one of the fibre end faces, which reduces the coupling losses from generally almost 100\% to less than 1\%. Since the decay function of the back and forth reflected pulses is acquired through the same micro hole, a compact bi-directional module can be used for pulse transmission and acquisition, consisting of a low power uncooled laser source and a fast photodiode detector. By choosing the cavity length to be longer than the pulse width, wavelength tuning of the pulses can be omitted resulting in a simplified hardware setup. Thus, the novel fibre-cavity design facilitates ring-down experiments and considerably reduces the cost of the associated sensor applications.

1. INTRODUCTION

Since ring-down experiments are applied to optical fibres, many different approaches regarding the design of fibre-cavities were published. Early investigations by Stone and Marcuse\textsuperscript{1} comprised highly reflective external mirrors, which were placed adjacent to the polished fibre ends but this method turned out to be susceptible to external vibrations. Later on, metallic coatings were directly vapour-deposited to the fibre end faces,\textsuperscript{2} resulting in reduced mirror coupling losses and a lower sensitivity to mechanical vibrations. In a similar approach these metallic coatings were replaced by multilayer dielectric coatings applied to determine bending losses of optical fibres\textsuperscript{3} and for evanescent-field sensing,\textsuperscript{4,5} for instance. To overcome the drawback of surface roughness due to imperfect polishing of the fibre ends, fibre bragg gratings were used as reflective elements and applied to refractive index sensing\textsuperscript{6} and microfluid monitoring.\textsuperscript{7,8} Another promising approach, using fibre-loops (fibre-ring cavities) instead of reflective layers, have been the subject of many publications to date, being applied to numerous sensing purposes such as refractive index measurements,\textsuperscript{9} trace gas detection,\textsuperscript{10} pressure,\textsuperscript{11,12} strain,\textsuperscript{13} temperature,\textsuperscript{14} and force sensing\textsuperscript{15} as well as for fluid monitoring.\textsuperscript{16,17}

A major drawback that all the above approaches have in common is an almost 100\% coupling loss when launching light into the cavity, either through the reflective layers (R\textgreater{}99.9\%) or by using couplers of high split ratios (e.g. 99:1). Since the photodetector is located behind the second mirror of the same reflectivity, a maximum of about 1/10000 of the initial pulse intensity can be detected in the case of passive non resonant cavities (pulse width shorter than the cavity length). This received intensity is even less with each round trip but the high reflectivities are necessary to achieve large numbers of round trips. Thus, pulses of high intensity and highly sensitive photodetectors such as photo multiplier tubes are used, accompanied by a number of further quite bulky and expensive devices such as an EDFA (in fibre-loops) and a high sampling rate scope.\textsuperscript{9,10} Although ringdown methods have shown great potential for high sensitivity detection, their use to date has been confined largely to the research laboratories. For this reason, our major concern was to design a fibre-cavity that reduces the hardware requirements with respect to pulse intensity and receiver sensitivity to make all the potential application above widely applicable.
2. RESULTS

The significant decrease of the coupling loss of the incident laser pulse was achieved using a multimode fibre-cavity whose end faces are Au coated. The single mode of a laser diode source was launched into the multimode cavity through a micro hole of 10um diameter that was milled into the coating of one of the two fibre end faces (fig. 1) using focussed ion beam technology. The parameters of the 20m long Polymer Clad Silica (PCS) fibre the cavity consists of are as follows: Core diameter = 400um, NA = 0.4, core refractive index = 1.457, cladding refractive index = 1.401, step index profile.

Once the pulse was coupled into the multimode fibre, many modes were excited by the incident single mode which is the basic principle upon which the proposed fibre-cavity is based. Fig. 2 shows this principle using the model of light as rays propagating on a zig-zag path along the fibre core. In fig. 3, the excitement of higher order modes is shown by means of the electric field distribution versus the fibre core radius at different distances from the coupling point using a two-dimensional simulation approach. It can be seen that with increasing distance the intensity decreases in the centre region of the core but the pulse is broadening, resulting in an electric field that spreads the entire fibre core after just a few millimeters. If such a field distribution strikes the coating that includes the micro hole then it is clear that just the intensity in the centre of the core leaves the cavity but the majority of the light energy is reflected by the coating that surrounds the micro hole. Thus, the greater the quotient of the fibre core diameter and that of the hole, the more reflections can be achieved. After a pulse is reflected and the intensity in the centre of the core is lost, energy exchange between adjacent modes then results in a 'uniform' field distribution again after a few millimeters but with a decreasing amplitude.

Since the light is coupled into the cavity through the same hole as it is detected, a compact bi-directional module as indicated in fig. 2 is intended to be used as combined laser source and receiver. Initial measurements to prove the principle of operation of the novel fibre-cavity design were performed using an OTDR. A 'dummy' fibre of 1km length was used to avoid so called ghosts between or overlayed with the decaying pulses. The resulting OTDR trace is shown in fig. 4, starting with the first received pulse that was reflected by the cavity. A decay of the pulse peaks is observable but they do not fade off to noise level as can be seen in the full OTDR trace of fig. 5. We believe that this effect is due to the influence of the dummy fibre whose entire trace appears after one 1km again. Consequently, the shape of the decay function could be disturbed, e.g., additional pulses of lower intensity may be overlayed by the offset and thus do not appear in the graph. For this reason, further investigations using an improved sampling circuit are in progress and will available soon.

Any suitable sensor probe (tapers etc.) or open path cells (microfluid or gas cells) can be placed in between the reflective fibre ends with the result that any change in the decay time of the decreasing pulse peaks is an indicator of the concentration of the measurand.

The intensity $I_x$ of the first detected pulse can be calculated by considering the following. After being launched into the cavity, the pulse of intensity $I_0$ propagates along the fibre of length $L$ and is attenuated by its attenuation coefficient $\alpha$. Reaching the second reflective coating of reflectivity $R_2$, an appropriate amount of the pulse intensity is reflected and passes the fibre of length $L$ again. Reaching the initial launching point, the photo receiver acquires the intensity that passes the first reflective coating of transmission $T_1 = 1 - R_1$ so that the intensity after the first round trip can be written as

$$I_x = I_0 (1 - R_1) R_2 e^{-2\alpha L}$$  \hspace{1cm} (1)
Thereby, $R_1$ not only represents the reflectivity of the coating itself but includes the losses caused by the micro hole as well, thus, $R_1$ describes the reflectivity of the entire fibre end face. Since $I_x$ represents the first detected peak, it also represents the point at which the ring-down trace starts. For each full round trip of the pulse from that point on, its intensity further decreases by an additional factor of $R_1 R_2 e^{-2\alpha L}$, so that the pulse intensity after a random number of round trips $n$ yields

$$I_n = I_x \left( R_1 R_2 e^{-2\alpha L} \right)^n \approx I_x e^{-n(\ln(R_1 R_2)+2\alpha L)}$$

(2)

In terms of calculating the time the pulse travelled through the cavity until being detected after each round trip, the discrete variable $n$ can be substituted by a continuous time variable $t = 2nL/c$, where $c$ is the speed of light in the optical fibre which is the ratio of the free space speed of light $c_0$ and the refractive index of the fibre core $n_{co}$. Consequently, $n$ in equation 2 can be replaced by $c_0 t / 2n_{co} L$ resulting in equation 3 which now is dependent on time.

$$I(t) = I_x e^{-\frac{t}{\tau}} \approx I_x e^{-\frac{c_0 t}{2n_{co} L} (\ln(R_1 R_2)+2\alpha L)}$$

(3)

Assuming such a single exponential decay function, it is clear from equation 3 that the decay time constant of the fibre-cavity yields

$$\tau = \frac{2n_{co} L}{c_0 (\ln(R_1 R_2)+2\alpha L)}$$

(4)

In the case of a present sensor element with an active length of $L_1$, an additional loss of $\alpha_1$ will be induced into the cavity (equation 5) resulting in a faster decaying ring-down curve.

$$\tau_1 = \frac{2n_{co} L}{c_0 (\ln(R_1 R_2)+2\alpha L+2\alpha_1 L_1)}$$

(5)

A more detailed investigation of the losses of the reflective coatings with respect to the ratio of micro hole diameter to fibre core diameter is also in progress.

3. CONCLUSION

It was shown that the coupling losses of fibre-cavities can be significantly reduced from almost 100% to less than 1% by using the proposed multimode cavity design. A major advantage of the decreased losses has been the ability to use standard non-cooled laserdiodes resulting in a rigorous cost reduction and potential miniaturisation and improved robustness of the system. Common photodiodes with low feedback resistors can be applied which increases the system stability compared to large resistor values. Finally, multimode sensors generally achieve higher sensitivities than their single mode counterparts due the presence of more modes that interact with the measurand.
REFERENCES


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