Reducing polarization mode dispersion with controlled polarization rotations

S Massar\textsuperscript{1,4} and S Popescu\textsuperscript{2,3}

\textsuperscript{1} Laboratoire d’Information Quantique, CP 225, Université Libre de Bruxelles, Boulevard du Triomphe, 1050 Bruxelles, Belgium
\textsuperscript{2} H H Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK
\textsuperscript{3} Hewlett-Packard Laboratories, Stoke Gifford, Bristol BS12 6QZ, UK
E-mail: smassar@ulb.ac.be and S.Popescu@bris.ac.uk

\textit{New Journal of Physics} 9 (2007) 158
Received 30 March 2007
Published 1 June 2007
Online at http://www.njp.org/
doi:10.1088/1367-2630/9/6/158

Abstract. One of the fundamental limitations to high bit rate, long distance telecommunication in optical fibres is polarization mode dispersion (PMD). Here we introduce a conceptually new method to reduce PMD in optical fibres by carrying out controlled rotations of polarization at predetermined locations along the fibre. The distance between these controlled polarization rotations must be less than both the beat length and the correlation length of the birefringence of the fibre. This method can also be combined with the method in which the fibre is spun while it is drawn.

Contents

1. Introduction 2
2. Polarized light propagating in optical fibres 3
3. Basic principle of the method 4
4. Combining controlled polarization rotations and spun fibres 5
5. Imperfections 6
6. Conclusion 7
Acknowledgments 8
References 8

\textsuperscript{4} Author to whom any correspondence should be addressed.
1. Introduction

Polarization mode dispersion (PMD) arises when two orthogonal states of polarization propagate at different velocities in optical fibres. PMD distorts the shape of light pulses, and in particular induces pulse spreading. Thus it fundamentally limits the performance of communication in fibre optics systems, and much effort has gone into reducing it, see [1, 2] for reviews. With the advent of 40 Gbit s$^{-1}$ long distance telecommunication, PMD is once more becoming a fundamental limitation, and new methods to reduce it are required.

PMD arises because of uncontrolled stresses or anisotropies induced in the fibre during the manufacturing process and during deployment. These cause unwanted birefringence, and hence PMD. This residual birefringence changes randomly along the fibre, resulting in random mode coupling as the light propagates along the fibre. Because of this statistical process, the effects of PMD—such as pulse spreading—increase as the square root of the propagation distance [3]–[8]. This statistical process makes it very difficult to correct the effects of PMD after light has propagated through a long length of fibre. For this reason one rather tries to reduce the PMD of the fibre itself.

The simplest way to reduce PMD in optical fibres is to minimize asymmetries in the index profile and stress profile of the fibre. To this end the manufacturing process has been steadily improved. A second method is to spin the fibre during the manufacturing process as described in [9, 10]. Spinning does not reduce the anisotropies in the fibre. Rather it modifies the orientation of the anisotropies along the fibre in such a way that after one spin period the effective birefringence and PMD is reduced. The effects of spinning on PMD were analysed in e.g. [11]–[16]. Residual birefringence can be characterized by the beat length $L_B$ and the correlation length of the birefringence, both of which in present day fibres are of the order of 10 m [17, 18].

In the present work we introduce a conceptually different method for reducing PMD in optical fibres. Our basic idea is to introduce controlled polarization rotations at predetermined locations along the fibre in such a way that the effects of PMD are reduced. This is paradoxical since the aim is to reduce birefringence and PMD, and we claim to achieve this by introducing additional polarization rotations. Our main idea is that after several such controlled polarization rotations, the state of polarization of the light has been oriented along many different directions on the Poincaré sphere in such a way that the effects of the fibre birefringence averages out. We will show that this can be highly effective. It can also be combined with the method of spinning the fibre.

We will not be concerned here with the details of how the controlled polarization rotations should be implemented in practice. Rather we are interested in presenting the principle of the method. We note however that there are many ways to induce controlled birefringence in fibres, and hence controlled polarization rotations, typically by inducing stress in the fibre. Such controlled stresses can obtained by compressing the fibre, twisting it, by anisotropic cooling of the fibre while it is drawn, by photosensitizing parts of the fibre with UV light, etc. These have to be implemented only with moderate precision, and could therefore be automatically implemented in the fibre during the fabrication process.

The method presented here for reducing PMD in optical fibres is inspired by the pulse sequences (e.g. spin echo) that have been developed in nuclear magnetic resonance (NMR) to reduce the effects of imperfections, see for instance [19]. These two problems can be mapped one onto the other, as the evolution of the state of polarization in an optical fibre is described.
by the same equations as the evolution of a spin in a magnetic field [20]. Our method is also related to the ‘bang–bang’ technique introduced by Viola and Lloyd to reduce decoherence in the context of quantum information [21, 22]. Wu and Lidar [23] suggested applying bang–bang control to reduce losses in optical fibres through controlled phase shifts, but their proposal is impractical because the control operations need to be implemented over distances comparable to the wavelength of light. On the other hand in the present case the control operations need to be implemented over distances of the order of 1 m, which makes it a much more practical proposal. An important conceptual difference is that in the bang–bang technique one wishes to average to zero the coupling between the system and the environment, whereas in the present case it is the coupling between the polarization and frequency of light itself, i.e. two degrees of freedom of the same system, which one wishes to average to zero.

2. Polarized light propagating in optical fibres

Consider a light pulse propagating along a birefringent optical fibre. The pulse is centred on frequency $\Omega$ and has wavenumber $K$. The distance along the fibre is denoted $l$. Its amplitude can be written as

$$A(l, t) e^{-i\Omega t + iKl},$$

where the slowly varying envelope of the pulse

$$A(l, t) = \begin{pmatrix} A_1(l, t) \\ A_2(l, t) \end{pmatrix}$$

is a two component vector, called the Jones vector, which describes the polarization state of the light. We introduce the variable $t' = t - l/v_g$ where $v_g$ is the group velocity of the pulse, whereupon $A$ obeys the evolution equation

$$i\partial_l A = B_0(l) A + iB_1(l) \partial_{t'} A,$$

where $B_0$ and $B_1$ are traceless, hermitian matrices describing the birefringence and PMD along the fibre. (The parts of $B_0$ and $B_1$ proportional to the identity are incorporated into the wavevector $K$ and the average group velocity $v_g$. For simplicity we neglect loss, dispersion, and nonlinearities.) The term proportional to $B_0$ describes the phase birefringence. Its magnitude is generally measured by the beat length $L_B = \pi/|B_0|$ which is the length after which the polarization is brought back to its original state. If only $B_0$ was present in the fibre, the state of polarization would evolve in an unknown way, but there would be no pulse spreading. The PMD is encoded in the group birefringence $B_1$ which describes the difference in group velocities of the two orthogonal states of polarization. This term will give rise to spreading of pulses. The birefringence changes along the fibre, hence both $B_0(l)$ and $B_1(l)$ depend on the position $l$ along the fibre. In present day low birefringence fibres both $L_B$ and the distance over which $B_0$ and $B_1$ change are comparable and of the order of 10 m [17, 18].

We can rewrite these matrices as

$$B_0(l) = \vec{B}_0(l) \cdot \vec{\sigma} \quad \text{and} \quad B_1(l) = \vec{B}_1(l) \cdot \vec{\sigma},$$

New Journal of Physics 9 (2007) 158 (http://www.njp.org/)
where
\[
\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}
\]
are the Pauli matrices, and \(x, y, z\) denote orthogonal directions on the Poincaré sphere. Denoting by \(A(l, \omega)\) the Fourier transform of \(A(l, t')\) with respect to \(t'\), equation (2) becomes
\[
i \partial_l A(l, \omega) = \vec{B}(l, \omega) \cdot \vec{\sigma} A(l, \omega),
\]
where
\[
\vec{B}(l, \omega) = \vec{B}_0(l) + \omega \vec{B}_1(l)
\]
is the sum of the birefringence and PMD in the fibre. The solution of equation (4) can be expressed as
\[
A(l, \omega) = U(l, \omega) A(0, \omega)
\]
with \(U(l)\) a \(2 \times 2\) unitary matrix, called the Jones matrix which describes the evolution of the state of polarization after propagating a distance \(l\).

3. Basic principle of the method

For simplicity we will first suppose in the following paragraphs that \(\vec{B}(l, \omega) = \vec{B}(\omega)\) is independent of \(l\), whereupon the Jones matrix is
\[
U(l) = e^{-i\vec{B}(\omega) \cdot \vec{\sigma} l}.
\]
Let us now show that, even though we do not know \(\vec{B}(l, \omega)\), it is possible to compensate for its effect so that after compensation the polarization comes back to its initial state. The following procedure consisting of four basic steps that are then repeated, realizes this.

1. The light propagates over distance \(l\). The distance \(l\) is taken short enough such that \(|B|l \ll 1\), hence the evolution can be well approximated by the first-order approximation:
\[
U(l) \approx 1 - i\vec{B}\vec{\sigma} l = 1 - il(B_x\sigma_x + B_y\sigma_y + B_z\sigma_z).
\]

2. We interrupt the evolution by flipping the polarization around the \(x\)-axis. We then let the light evolve over a new distance \(l\) and finally we flip the polarization around the \(x\)-axis again. The evolution in step 2 is thus described by \(\sigma_x U(l)\sigma_x\). To first order in \(|B|l\), one finds
\[
\sigma_x U(l)\sigma_x \approx \sigma_x (1 - i\vec{B}\vec{\sigma} l)\sigma_x = 1 - il(B_x\sigma_x - B_y\sigma_y - B_z\sigma_z)
\]
which effectively compensates the evolution due to the \(B_y\) and \(B_z\) components. The evolution due to the \(B_x\) component is not yet compensated; this will be accomplished during the next two steps.

3. The same as step 2, but the spin is flipped around the \(y\)-axis. Step 3 is thus described by \(\sigma_y U(l)\sigma_y\). By expanding \(U(l)\) to first order we obtain
\[
\sigma_y U(l)\sigma_y \approx \sigma_y (1 - i\vec{B}\vec{\sigma} l)\sigma_y = 1 - il(-B_x\sigma_x + B_y\sigma_y - B_z\sigma_z).
\]
4. The same as step 2, but the spin is flipped around the \( z \)-axis. Step 4 is thus described by \( \sigma_z U(l) \sigma_z \). To first order we obtain

\[
\sigma_z U(l) \sigma_z \approx \sigma_z (1 - i\vec{B}\sigma) = 1 - i\vec{B}(\sigma_x, \sigma_y, \sigma_z).
\]

Putting everything together, the time evolution over the four steps is

\[
U(l_{\text{seq}}) = \sigma_z U(l) \sigma_z \sigma_y U(l) \sigma_z U(l) \sigma_x U(l)
\]

\[
= 1 + O(B^2 l^2_{\text{seq}}),
\]

where we denote by \( l_{\text{seq}} = 4l \) the length of the sequence. The evolution is therefore effectively stopped. The procedure is then repeated again and again. Note that because \( \sigma_z \sigma_x = i\sigma_x \), equation (12) simplifies to

\[
U(l_{\text{seq}}) = \sigma_z U(l) \sigma_x U(l) \sigma_z U(l) \sigma_x U(l).
\]

The method relies on the fact that the interaction, although unknown to us, does not change along the fibre (at least for the short lengths \( l_{\text{seq}} \) we are considering here). The unknown birefringence \( \vec{B} \) that is responsible for the rotation of the polarization in the first place is there all the time, and affects the polarization after the \( x \)-, \( y \)- and \( z \)-rotations, and brings it back to its initial state at the end of the sequence.

In optical fibres the phase birefringence is of the same order as the group birefringence. This implies that \( B_0/\Omega \simeq B_1 \). Since \( \omega \), the frequency spread of the pulse, is much smaller than \( \Omega \), the carrier frequency, we can expand equation (13) to first order in \( \omega B_1 \) to obtain

\[
U(l_{\text{seq}}) = 1 + O(B_0^2 l_{\text{seq}}^2) + O(\omega B_1 B_0 l_{\text{seq}} L)
\]

where \( l_{\text{seq}} = 4l \). It is given by \( U(L) = U(l_{\text{seq}}) L/l_{\text{seq}} \simeq 1 + O(B_0^2 l_{\text{seq}} L) + O(\omega B_1 B_0 l_{\text{seq}} L) \) whereas in the absence of the control sequence it would have been given by \( 1 + B_0 L + \omega B_1 L \). Hence there is a reduction of PMD by a factor \( B_0 l_{\text{seq}} = \pi l_{\text{seq}} / L_B \).

Note that as shown in [22] it is possible to devise sequences that cancel not only the terms of order \( B l \), but higher order terms as well. For instance the sequence

\[
U_2(l_{\text{seq}}) = U(l) \sigma_x U(l) \sigma_z U(l) \sigma_x U(l) \sigma_z U(l) \sigma_x U(l) \sigma_z U(l) \sigma_x U(l) = 1 + O(B^3 l_{\text{seq}}^3)
\]

cancels the evolution up to order \( B^3 l^3 \).

4. Combining controlled polarization rotations and spun fibres

It is possible to reduce PMD in optical fibres by combining the methods of controlled polarization rotations and of spinning the fibre while it is drawn. Here we first show how to include both methods in a unified description, and then we discuss how they can be used in combination.

For spun fibres the evolution equation is no longer given by equation (4), but by

\[
i\partial_t A = U_{\text{spin}}^\dagger(l) B(\omega) U_{\text{spin}}(l) A,
\]

where \( B(\omega) = \vec{B}(\omega) \cdot \vec{\sigma} \) and

\[
U_{\text{spin}}(l) = e^{-i\sigma(l)\sigma_z}. \tag{17}
\]
describes the spin of the fibre, \( \alpha(l) \) is the spin function (the angle by which the fibre is spun), and \( \sigma_z \) is the Pauli matrix that generate polarization rotations around the circular polarization axis. To first order in \( B \) the evolution is given by

\[
U(l) = 1 + i \int_0^l d\ell' U^\dagger_{\text{spin}}(\ell') B(\omega) U_{\text{spin}}(\ell'),
\]

from which one deduces, see [13], that in order to reduce PMD the spin function must obey

\[
\int_0^L dl \cos \left[ \int_0^l 2\alpha(\ell') d\ell' \right] = 0 \quad \text{and} \quad \int_0^L dl \sin \left[ \int_0^l 2\alpha(\ell') d\ell' \right] = 0 \quad (18)
\]

where \( L \) is the spin period (the period of \( \alpha(l) \)). Note that spinning the fibre alone can reduce linear birefringence, but not circular birefringence (proportional to \( \sigma_z \)).

If we incorporate controlled polarization rotations, we get the evolution equation:

\[
i \partial_l A(l) = \left( U^\dagger_{\text{spin}}(l) B(\omega) U_{\text{spin}}(l) + B_c(l) \right) A \quad (19)
\]

where \( B_c(l) \) describes the (smooth or instantaneous) controlled polarization rotations. It is convenient to rewrite this equation in the frame that rotates with the spin. To this end we define \( \tilde{A}(l) = U_{\text{spin}}(l) A(l) \). The rotated Jones vector obeys the evolution equation

\[
i \partial_l \tilde{A} = \left( B(\omega) + \partial_l \alpha(l) \sigma_z + U_{\text{spin}}(l) B_c(l) U^\dagger_{\text{spin}}(l) \right) \tilde{A}. \quad (20)
\]

Thus in the rotating frame, spin is formally identical to a continuous controlled polarization rotation given by \( \partial_l \alpha(l) \sigma_z \), whereas the controlled polarization rotations \( B_c(l) \) are rotated and take the form \( U_{\text{spin}}(l) B_c(l) U^\dagger_{\text{spin}}(l) \). Therefore even though they have completely different origins, they can easily be combined. For instance one easily checks that by carrying out a \( \sigma_x \) flip of polarization after each spin period one cancels both linear and circular birefringence.

### 5. Imperfections

In the above paragraphs we considered an ideal situation in which the polarization rotations are perfect, and the birefringence of the fibre constant. However in practice imperfections will arise which will compromise the efficiency of the method. We discuss these briefly.

First of all we note that carrying out instantaneous polarization rotations (the \( \sigma_x, \sigma_y, \sigma_z \) rotations of section 3) is in practice impossible, and that these rotations will always be implemented over a finite length. In this case the residual birefringence \( \tilde{B}(\omega) \) that occurs over this length will modify the rotation in an uncontrolled way. This will introduce an error and diminish the efficiency of the method. Of course if the polarization rotation is carried out over a very short length of fibre this effect may be sufficiently small to be negligible.

However a more elegant way to circumvent this problem is to consider explicitly that the control rotations are implemented gradually. Such smooth control polarization rotations will be described mathematically by a birefringence \( \tilde{B}_c(l) \). The evolution equation (4) must then be replaced by

\[
i \partial_l A(l, \omega) = \tilde{B}(l, \omega) \cdot \tilde{\sigma} A(l, \omega) + \tilde{B}_c(l) \cdot \tilde{\sigma} A(l, \omega), \quad (21)
\]
which in the case of spun fibres leads to equation (19). (Note that if one takes \( \vec{B}_c(l) \) to be proportional to \( \delta \)-functions, one recovers the case of instantaneous rotations.) It is not difficult to exhibit smooth, bounded functions \( \vec{B}_c(l) \) for which the PMD is compensated to first order, exactly as for instantaneous polarization rotations.

Secondly we should take into account that the unknown polarization rotation \( \vec{B} \) changes slowly along the fibre. The characteristic length over which the polarization changes \( \left( \frac{\partial l}{B} \right)^{-1} \) is related to the correlation length introduced in [8] and measured in [17, 18]. Obviously the length of the sequence must be less than the correlation length, otherwise the compensation which occurs between the different steps in section 3 will no longer be obtained. It should be possible in future work to develop a more quantitative approach by taking \( \vec{B}(l) \) to be a smooth function which can be expanded in Taylor series \( \vec{B}(l) = \vec{B}(0) + l \partial_l \vec{B}(0) + O(l^2) \) and then inserting this expression into equation (7).

A third source of imperfection is that the controlled polarization rotations themselves will not be achromatic, and will therefore themselves introduce PMD. Thus, instead of carrying out the rotation \( \sigma_x \), one carries out the rotation \( \exp[i \sigma_x \pi(1 + \omega \beta)/2] \) where \( \beta \approx B_1 / B_0 \approx \Omega / \Omega_1 \). It is thus necessary to cancel the PMD due to \( \beta \). To do this we suggest using the well known idea of stacking several chromatic waveplates to yield an essentially achromatic waveplate [24].

A final limitation is that the angle of the controlled polarization rotations is not perfectly controlled, and will vary slightly in a random way. Thus instead of implementing \( \sigma_x \) one implements \( \exp[i(\pi \sigma_x + \vec{r} \cdot \vec{\sigma})/2] \) where \( \vec{r} \) is a small random vector.

As an illustration of the effects of these imperfections we have done a rough estimate in the simple case where the residual PMD is characterized by length scales \( L_B \approx L_{\text{corr}} \approx 10 \text{ m} \) (where \( L_{\text{corr}} = \frac{[\vec{B}(0)]}{[\partial_l \vec{B}(0)]} \)) and we correct for the PMD using the simple sequence of polarization rotations equation (14). In order to cancel the PMD of the polarization rotations themselves, we replace each \( \pi \) rotation by an achromatic triplet of \( \pi \) rotations. Assuming \( r = 1/30 \), and inserting omitted numerical constants, we find that the PMD is reduced by approximately a factor of five for \( l_{\text{seq}} = L_B / 7 \). Thus in this simple example the polarization rotations must be implemented approximately every 12 cm.

This estimate shows that with moderately precise polarization rotations, implemented over reasonable length scales, one can significantly reduce the PMD in optical fibres. We expect that significant improvement of this preliminary result is possible, as it should be possible to apply the methods used in NMR to systematically optimize pulse sequences to the present problem.

6. Conclusion

We have presented a method to reduce PMD in optical fibres based on the use of controlled polarization rotations. The results presented here are only a first study of the potentialities of the method, and we expect that significant improvements of the sequences presented here can be achieved by using the same methods which are successfully used to optimize pulse sequences in NMR. The method presented here can be combined with the well-established method of spinning the fibre. The efficiency of the combined method will depend on the detailed properties of the residual birefringence in the fibres, such as the beat length and correlation length, and on the precision with which the controlled polarization rotations can be implemented. In addition to the important application for long distance, high speed telecommunication in optical fibres, this
method may find applications in other communication systems in which one wants to reduce unwanted birefringence. Finally, on the conceptual side, our work provides a simple system in which to test the ideas of bang–bang control.

Acknowledgments

We acknowledge financial support by the Interuniversity Attraction Poles Programme—Belgium Science Policy—under grants V-18 and VI-10; and by the European Commission IST programme under project RESQ IST-2001-37559 and project Qubit Applications (QAP) contract number 015848.

References

[1] Nolan D A, Chen X and Li M-J 2004 Fibres with low polarization-mode dispersion IEEE J. Lightw. Technol. 22 1066–77
[2] Galtarossa A and Menyuk C R (ed) 2005 Polarization Mode Dispersion (Berlin: Springer)
[3] Poole C D 1988 Statistical treatment of polarization dispersion in single-mode fibre Opt. Lett. 13 687
[4] Poole C D 1989 Measurement of polarization-mode dispersion in single-mode fibres with random mode coupling Opt. Lett. 14 523
[5] Poole C D, Winters J H and Nagel J A 1991 Dynamical equation for polarization dispersion Opt. Lett. 16 372
[6] Gisin N, Von Der Weid J P and Pellaux J P 1991 Polarization mode dispersion of short and long single mode fibres IEEE J. Lightw. Technol. 9 821–7
[7] Gisin N and Pellaux J P 1992 Polarization mode dispersion time domain versus frequency domain Opt. Commun. 89 316–23
[8] Wai P K A and Menyuk C R 1996 Polarization mode dispersion, decorrelation, and diffusion in optical fibres with randomly varying birefringence J. Lightw. Technol. 14 148
[9] Barlow A J, Ramskov-Hansen J J and Payne D N 1981 Birefringence and polarization mode-dispersion in spun single-mode fibres Appl. Opt. 20 2962
[10] Hart A C Jr, Huff R G and Walker K L 1994 Method of making a fibre having low polarization mode dispersion due to a permanent spin US patent 5298047
[11] Li M J, Nolan D A 1998 Fibre spin-profile designs for producing fibres with low polarization mode dispersion Opt. Lett. 23 1659–61
[12] Schuh R E, Shan X and Siddiqui A S 1998 Polarization mode dispersion in spun fibres with different linear birefringence and spinning parameters IEEE J. Lightw. Technol. 16 1583
[13] Chen X, Li M J and Nolan D A 2002 Polarization mode dispersion of spun fibres: an analytical solution Opt. Lett. 27 294–6
[14] Chen X, Li M J and Nolan D A 2002 Scaling properties of polarization mode dispersion of spun fibres in the presence of random mode coupling Opt. Lett. 27 1595–7
[15] Galtarossa A, Palmieri L, Pizzinat A, Marks B S and Menyuk C R 2003 An analytical formula for the mean differential group delay of randomly birefringent spun fibres IEEE J. Lightw. Technol. 21 1635
[16] Pizzinat A, Palmieri L, Marks B S, Menyuk C R and Galtarossa A 2003 Analytical treatment of randomly birefringent periodically spun fibres IEEE J. Lightw. Technol. 21 3355
[17] Galtarossa A, Palmieri L, Schiano M and Tambosso T 2000 Measurements of beat length and perturbation length in long single-mode fibres Opt. Lett. 25 384
[18] Galtarossa A, Palmieri L, Schiano M and Tambosso T 2001 Measurement of birefringence correlation length in long, single-mode fibres Opt. Lett. 26 962–4
[19] Slichter C P 1990 Principles of Magnetic Resonance 3rd edn (New York: Springer)
[20] Lin Q and Agrawal G P 2005 Intrapulse depolarization in optical fibres: a classical analog of spin decoherence
   Opt. Lett. 30 821–3
[21] Viola L and Lloyd S 1998 Dynamical suppression of decoherence in two-state quantum systems Phys. Rev. A
   58 2733–44
[22] Viola L, Knill E and Lloyd S 1999 Dynamical decoupling of open quantum systems Phys. Rev. Lett. 82 2417–21
[23] Wu L-A and Lidar D A 2004 Overcoming quantum noise in optical fibres Phys. Rev. A 70 062310
[24] Pancharatnam S 1955 Achromatic combinations of birefringent plates Proc. Indian Acad. Sci. A 41 137–44
Corrigendum added 5 September 2007

On page 3, when discussing reference [23] by Wu and Lidar, it is stated that their proposal is impractical because the control operations need to be implemented over distances comparable to the wavelength of light. We would like to point out that this does not reflect the statements made in [23], but rather the opinion of the authors of the present paper. Indeed in [23] it is argued that the control operations can be implemented over much larger distances.