# Intrusion Detection Based on Quantum Interference

**Clifford Allen Bishop**[1], **Travis S. Humble**[1], **Ryan S. Bennink**[1], **and Brian P. Williams**[1,2]

[1] *Quantum Information Science Group, Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6418, USA*

[3] *Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200, USA*

*bishopca@ornl.gov*

**Abstract:** We present a new method for intrusion detection which is based on the Mach-Zehnder interference effect. This device provides monitored surveillance by continuously measuring the intensity of light collected by a pair of photodetectors.

© 2013 Optical Society of America

**OCIS codes:** 000.0000, 999.9999.

## 1. Introduction

In these proceedings, we present a new method for intrusion detection which is based on the Mach-Zehnder interference (MZI) effect. This device provides monitored surveillance by continuously measuring the intensity of light collected by a pair of photodetectors. Under normal working conditions each photodetector output current per signal pulse is expected to remain ~~roughly~~ constant. When an intruder ~~simply~~ passes **through** the secured perimeter, the beam is blocked and the output signal drops ~~dramatically~~ signaling an alarm. This feature is shared with common laser tripwire designs. **However, a conventional trip wire device is vulnerable to intruder attempts to fool the detection systems, for example, by using path diversion or intercept-resend techniques. Our contribution attempts to close this vulnerability by using MZI to test the integrity and authenticity of the transmitted signal and thereby offer an additional layer of security relative to classical optical sensors.**

## 2. Normal operation

An illustration of our proposal is given in Fig. 1. The setup consists of a balanced **MZI = Mach-Zehnder interference** with a photon source located at input port $\hat{s}$. The left $L$, top $T$, and right $R$ arms of the interferometer constitute the ~~fence~~ **secured** perimeter while regions specified with a shaded box are assumed to be secure **enclaves**. We assume a balanced configuration under normal operating conditions. The phase shifts $\phi_1$ and $\phi_2$ are included for security purposes and will be discussed shortly. The source mode $\hat{s}$ is ~~associated~~ **populated** with the signal mode of a down-conversion process [1,2]. The idler mode $\hat{i}$ (not shown in the figure) ~~will then~~ serves as a herald for ~~MZI~~ **signal** photon injection. Let the $j$th idler photon be detected at time $t = t_j$. At this moment, the state of the signal field is given by

$$|\Psi\rangle_{s,j} = (2\beta/\pi)^{1/4}\sqrt{\frac{\pi}{\beta}}\int dt e^{-2\pi i t(\omega_p/2)} e^{-\pi^2 t^2/\beta}\,\hat{s}^\dagger(t_j - t)\,|\text{vac}\rangle\,. \tag{1}$$

Here, $\omega_p$ denotes the pump frequency of a quasi-monochromatic pump and $\beta = 1/\sigma^2 - \gamma L^2 J^2/4$ **Your reusing $L$ here**. The idler pass band function is given by $e^{-(\omega-\omega_p/2)^2/\sigma^2}$, where $\sigma > 0$ is a real parameter. The crystal length is given by $L$, $\gamma = 0.193\ldots$, and $J = (k'_{\text{idler}}(\omega_p/2) - k'_{\text{signal}}(\omega_p/2))$. For now, let $\phi_1 = \phi_2 = 0$. The normal output flux at mode $\hat{w}_1$ can be readily evaluated for the input state $|\Psi\rangle_{s,j}$. We obtain

$$\langle \hat{w}_1^\dagger(t)\hat{w}_1(t)\rangle = (2\pi/\beta)^{1/2}\exp\left[-2\pi^2(t_j + t_0 - t)^2/\beta\right], \tag{2}$$

with $t_0$ representing the time required to travel the length of the bottom arm $B$. Let us suppose that the detector makes a measurement within a finite interval $T_R$ centered at time $t = t_j + t_0$. The expected photon number collected is thus

$$\mathscr{I}_0 = \int_{t_j+t_0-T_R/2}^{t_j+t_0+T_R/2} d\tau \langle \hat{w}_1^\dagger(\tau)\hat{w}_1(\tau)\rangle = \text{Erf}\left(T_R\pi/\sqrt{2\beta}\right) \tag{3}$$

The error function increases from zero to one as the factor $T_R/\sqrt{\beta} > 0$ increases. For $T_R \geq \sqrt{\beta}$, $\mathscr{I}$ takes the value of one. ~~**As $\sigma$ decreases the idler frequency pass-band becomes tighter resulting in a broader temporal spread of the signal photon.**~~

QL3.pdf

Fig. 1. Security protocol based on a balanced Mach-Zehnder interferometer.

## 3. Intrusion Techniques

Due to the straight line geometry of each branch, a path redirection from one point on a given branch $(L,T,R)$ to another point on that same branch will necessarily increase the optical path length. However, a path redirection from a point on one branch to a point on a different branch could in principle leave the total optical path length unchanged. In the first case we find

$$\begin{aligned}\langle \hat{w}_1^\dagger(t)\hat{w}_1(t)\rangle &= \sqrt{\frac{\pi}{8\beta}}\Big(e^{-2\pi^2(t_0+t_j-t)^2/\beta}+(e^{-i\xi}e^{2\pi i\Delta\omega_p/2}+e^{i\xi}e^{-2\pi i\Delta\omega_p/2})(e^{-\pi^2(t_0+t_j-t)^2/\beta}e^{-\pi^2(t_0+t_j-t+\Delta)^2/\beta})\\ &\quad +e^{-2\pi^2(t_0+t_j-t+\Delta)^2/\beta}\Big). \end{aligned} \tag{4}$$

Here $\Delta$ represents the additional flight time introduced as a result of the redirection, i.e., $\Delta = t_L + t_T + t_R - t_0$. The additional phase factor $\xi = 2\pi c\Delta/\lambda$ results from the additional path length, where $c$ is the speed of light and $\lambda$ is the wavelength of the $j$th photon. For example, with a pump beam centered at 400 nm, and with a detector resolving time of $T_R = \sqrt{\beta} = 0.1$ ns, we find that an additonal path lengh increase of $\geq 1$ cm results in a value of $\mathscr{I}_1 = \int_{t_j+t_0-T_R/2}^{t_j+t_0+T_R/2} d\tau\langle \hat{w}_1^\dagger(\tau)\hat{w}_1(\tau)\rangle$ equal to 1/4 of the normal value $\mathscr{I}_0$.

In the second case, where a path diversion occurs between separate branches, e.g., from $L$ to $T$, the intruder would do best by matching the diversion length to the original length. For this reason, we include random phase shifts $\phi_1$ and $\phi_2$ at the points along the **perimeter** where there is path redirection. The sequence of phase shift values in a particular location are assumed to be generated randomly before activation and stored as a string $\phi_i = (\phi_{i,1}, \phi_{i,2}, \phi_{i,3}, \ldots, \phi_{i,N})$ $(i = 1,2)$. Suppose the path lengths match and $\phi_{int}$ denotes the additional phase introduced by the intruder. Then, for a fixed $\phi_{i,j}$, we find the average of the quantity $\langle \hat{w}_1^\dagger(t)\hat{w}_1(t)\rangle$ over all $\phi_{int}$ and $t$ to be

$$\frac{1}{2\pi}\int_{\phi_{int}=0}^{2\pi}\int_{t=-\infty}^{\infty}\langle \hat{w}_1^\dagger(t)\hat{w}_1(t)\rangle dt d\phi_{int} = \frac{1}{2}. \tag{5}$$

On average, the flux at the output drops to 1/2 of the normal rate when a path diversion attempt of this sort occurs. A intercept-resend attack, i.e., a teleportation attack, is completely equivalent to the diversion attacks above due to the time required for the measurement and measurement outcome feed-forward stages.

## 4. Conclusions

In conclusion, we have presented a method of detecting intrusion across an optically defined perimeter using the MZI effect. Like earlier efforts employing related effects [3], a quantum optical sensor can mitigate the redirection and intercept-resent vulnerabilities facing their classical counterparts. We expect additional work will provide greater clarity into the sensing power of this approach, especially with respect to actively tampered optical seals.

## References


1. Z.Y. Ou, *Multi-Photon Quantum Interference*, (Springer, 2007).
2. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics*, (Cambridge, 1995).
3. T. S. Humble, R. S. Bennink, W. P. Grice and I. J. Owens, Proc. SPIE **7342**Proc. SPIE, 733402H (2009)


### *4.1. Author Names and Affiliations*

Author names should be given in full with first initials spelled out to assist with indexing. Affiliations should follow the format division, organization, and address—and complete postal information should be given. Abbreviations should not be used. United States addresses should end with “, USA.”

### *4.2. OCIS Subject Classification*

Two Optics Classification and Indexing Scheme (OCIS) subject classifications should be placed at the end of the abstract with the `\ocis{}` command. OCIS codes can be found at http://www.opticsinfobase.org/submit/ocis/.