Optics Communications 356 (2015) 620–627

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The performance of heterodyne detection system for partially coherent beams in turbulent atmosphere

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ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form
21 July 2015
Accepted 25 August 2015

Keywords:
Detection
Heterodyne
Atmospheric turbulence
Laser beam transmission

ABSTRACT

The performance of heterodyne system is discussed for partially coherent beams in turbulent atmosphere by introducing turbulence spectrum of refractive-index fluctuations. Several analytic formulae for the heterodyne detection system using the partially coherent Gaussian Schell-model beam are presented. Based on Tatarskii spectrum model, some numerical results are given for the variation in the heterodyne efficiency with the misalignment angle, detector diameter, turbulence conditions, and parameters of the overlapping beams. According to the numerical results, we find that the turbulent atmosphere degrades the heterodyne efficiency significantly, and the variation in heterodyne efficiency is even slower against the misalignment angle in turbulence. For the deterministic received signal and the detector, the performance of the heterodyne detection can be adjusted by controlling the local oscillator signal parameters.

1. Introduction

Heterodyne detection is a widely used technique in the microwave region. Heterodyne technique has been extended to the optical regions owing to its noise-reduction capabilities and high spectral resolution in comparison with incoherent (direct) detection [1]. Heterodyne (coherent) detection is a more powerful detection technique for long-range and weak signal detections [2]. At the same time, heterodyne detection system needs more stringent technical requirements than incoherent detection does. In order to ensure the performance of optical heterodyne detection system, the wavefront, amplitude and polarization of the local oscillator (LO) and signal beams should be matched strictly [3–5]. The wavefront alignment between signal and local oscillator beams required for effective optical heterodyne is treated by Siegman, which is summarized in the "antenna theorem" for optical heterodyne [6]. In order to obtain the high performance, it is necessary to match the locally generated beam parameters with the received signal beam parameters on the detector [7]. Heterodyne efficiency of the optical coherent detection system reflects the matching degree of phase and amplitude between the local oscillator and received signal beams [8]. The heterodyne efficiency is considered as a measurement to evaluate the performance of the heterodyne technique. It may also be used to quantify the potential mismatch between the locally generated signal and the received one [9]. The mismatch directly reduces the signal-to-noise ratio (*SNR*) of the detection system.

The performance of the heterodyne system for spatially fully coherent signals has been investigated in previous works. The effect of atmospheric turbulence on the heterodyne performance has been studied for coherent laser radar systems [10,11]. General expressions are derived for the *SNR* of a coherent detection system in terms of the deterministic received signal and local oscillator fields including the parameters of detector [12]. Tanaka and Saga considered the maximum heterodyne efficiency for an optical heterodyne detection system in the presence of background radiation [13]. The performance of an optical heterodyne detection system with aberrations is studied theoretically and experimentally [14,15].

However, most of the physically realizable optical sources radiate randomly due to the inhomogeneity in resonant cavity and the characteristics of spontaneous emission of the atoms [16,17]. On the other hand, the phase front will become chaotic after

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http://dx.doi.org/10.1016/j.optcom.2015.08.075

coherent radiation propagating through turbulent media. These reasons result in partially coherent radiation [18]. Hence, the performance of an optical heterodyne system for partially coherent beams should be treated thoroughly. Optical heterodyne detection of partially coherent cross-spectrally pure radiation is considered by Chiou [1]. Tanaka et al. studied the heterodyne efficiency for partially coherent optical signals [19]. The performance of a misaligned heterodyne detection system for partially coherent beams is treated by Salem and Rolland [20]. However, Salem and Rolland did not address the effects of atmospheric turbulence. The effects of turbulent atmosphere on the performance of heterodyne system cannot be ignored in practical applications. Based on the atmospheric coherence length or Fried parameter, Ren et al. discussed the performance of coherent free-space optical communication system [21]. It is feasible to employ various models of the power spectrum for atmospheric turbulence as an effective way to discuss the effects of atmosphere on the heterodyne system. However, the similar works have not been described in the previous treatments.

In this paper, the effects of turbulent atmosphere on the performance of heterodyne system are studied for partially coherent beams based on the turbulence spectrum of the refractive-index fluctuations [22]. General expressions that include turbulence spectrum for the heterodyne performance for mixing two partially coherent and quasi-monochromatic beams on a detector surface are obtained. The Tatarskii spectrum model is employed to investigate the effects of turbulent atmosphere on the performance of optical heterodyne detection system in this study. The Tatarskii spectrum improves the agreement between theory and experimental measurements by truncating the spectrum at high wave numbers in the presence of atmospheric turbulence [22]. For different cases, some numerical results are presented to show the performance of heterodyne system with different beam parameters under the influence of atmospheric turbulence. The effect of the misalignment angle on the heterodyne efficiency in turbulence is also investigated. Additionally, the joint effects of different conditions will be discussed in detail in the following.

2. Heterodyne performance of partially coherent beam

Although the local oscillator is typically coherent, we consider the local oscillator being partially coherent to obtain an expression that is applicable to the most general cases for the heterodyne efficiency including the coherence properties of the light source. Let us consider two quasi-monochromatic and partially coherent beams propagating to a detector located at $z=0$ plane in a Cartesian coordinate system. We further assume that the propagation direction of the local oscillator beam is perpendicular to the detector surface but with a misalignment angle θ between its direction and the propagation direction of received signal as shown in Fig. 1.

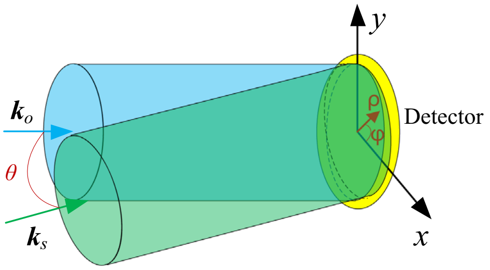

Fig. 1. The model of mixing two beams on a detector located at $z=0$ plane.

The instantaneous field of both signals at the detector surface can be expressed as

$$U_o(\boldsymbol{\rho},t)=U_o(\boldsymbol{\rho})e^{i\omega_o t} \tag{1}$$

$$U_s(\boldsymbol{\rho},t)=U_s(\boldsymbol{\rho})e^{i\omega_s t-i\boldsymbol{k}\cdot\boldsymbol{\rho}} \tag{2}$$

where ω_o and ω_s are the central angular frequencies of the signals and $\boldsymbol{k}$ is the wave vector of the received signal. The subscripts o, s denote the locally generated signal and received signal respectively. Based on the model of heterodyne detection [23], the detected intermediate frequency (IF) power can be given by the expression [20]

$$P_{IF}=\iint\iint 2\Re(\boldsymbol{\rho}_1)\Re(\boldsymbol{\rho}_2)\mathrm{Re}\left[\Gamma_o(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)\Gamma_s{}^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)e^{i\boldsymbol{k}\cdot\boldsymbol{\rho}_1-i\boldsymbol{k}\cdot\boldsymbol{\rho}_2}\right]d^2\boldsymbol{\rho}_1 d^2\boldsymbol{\rho}_2 \tag{3}$$

where $\Re(\boldsymbol{\rho})=e\eta(\boldsymbol{\rho})/h\nu$ is the detector responsivity at point $\boldsymbol{\rho}$, $\eta(\boldsymbol{\rho})$ is the quantum efficiency, e is the electronic charge, $h\nu$ is the photo energy, and $\Gamma_o(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)$ and $\Gamma_s(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)$ are the mutual coherence functions of the received and LO beams on the detector surface respectively [24]. The IF power is the useful part of the output of detector, and the other part of the output is random noise. The noise sources are of two types: those which depend on the power of local oscillator beam and those which are independent of the locally generated beam. Commonly, the standard shot-noise power of local oscillator field exceeds the other noises in the detection system and eventually becomes the dominant noise source. Assuming that the detector is operating at the shot-noise limit, the noise equivalent power could be defined as the shot-noise power of the local oscillator beam. The shot-noise power of the local oscillator beam is given by [23]

$$P_n=2eB\iint\Re(\boldsymbol{\rho})\Gamma_o(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho} \tag{4}$$

where B is the receiver bandwidth of the detector. Using the results of the IF power and shot-noise power, it is easy to derive the expression of SNR as [20,25]

$$SNR=\frac{\iint\iint 2\Re(\boldsymbol{\rho}_1)\Re(\boldsymbol{\rho}_2)\mathrm{Re}\left[\Gamma_o(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)\Gamma_s{}^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)e^{i\boldsymbol{k}\cdot\boldsymbol{\rho}_1-i\boldsymbol{k}\cdot\boldsymbol{\rho}_2}\right]d^2\boldsymbol{\rho}_1 d^2\boldsymbol{\rho}_2}{2eB\iint\Re(\boldsymbol{\rho})\Gamma_o(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho}} \tag{5}$$

Assuming that the detector responsivity $\Re$ is uniform across the detector surface and considering that those parameters do not affect the SNR variation, Eq. (5) can be further simplified as

$$SNR^{+}=\frac{\iint\iint \mathrm{Re}\left[\Gamma_o(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)\Gamma_s{}^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)e^{i\boldsymbol{k}\cdot\boldsymbol{\rho}_1-i\boldsymbol{k}\cdot\boldsymbol{\rho}_2}\right]d^2\boldsymbol{\rho}_1 d^2\boldsymbol{\rho}_2}{\iint\Gamma_o(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho}} \tag{6}$$

It is easy to see that the SNR^{+} is a normalized SNR, $SNR^{+}=SNReB/\Re$. The SNR^{+} variation depends on the beam parameters and detector diameter. Another useful measurement of heterodyne performance is the dimensionless heterodyne efficiency η_h, which measures the loss in coherent power when the received and LO field are not perfectly matched. The heterodyne efficiency for random fields is defined in an analogous manner to the case of deterministic fields, i.e. [20]

$$\eta_h=\frac{\iint\iint \Re(\boldsymbol{\rho}_1)\Re(\boldsymbol{\rho}_2)\mathrm{Re}\left[\Gamma_o(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)\Gamma_s{}^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)e^{i\boldsymbol{k}\cdot\boldsymbol{\rho}_1-i\boldsymbol{k}\cdot\boldsymbol{\rho}_2}\right]d^2\boldsymbol{\rho}_1 d^2\boldsymbol{\rho}_2}{\iint\Re(\boldsymbol{\rho})\Gamma_o(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho}\iint\Re(\boldsymbol{\rho})\Gamma_s(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho}} \tag{7}$$

Under the assumption that the detector responsivity $\Re$ is uniform across the detector surface, the heterodyne efficiency in this case can be expressed as

$$\eta_h=\frac{\iint\iint \mathrm{Re}\left[\Gamma_o(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)\Gamma_s{}^*(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)e^{i\boldsymbol{k}\cdot\boldsymbol{\rho}_1-i\boldsymbol{k}\cdot\boldsymbol{\rho}_2}\right]d^2\boldsymbol{\rho}_1 d^2\boldsymbol{\rho}_2}{\iint\Gamma_o(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho}\iint\Gamma_s(\boldsymbol{\rho},\boldsymbol{\rho})d^2\boldsymbol{\rho}} \tag{8}$$

Using Eqs. (6) and (8), one can express the SNR^{+} of the