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Enhancement of heterodyne efficiency of heterodyne LADAR system with APD array detector based on array lighting

Yang Chenghua, Zhang Yong, Zhao Yuan

(Department of Physics, Harbin Institute of Technology, Harbin 150001, China)

Abstract: At the moment non-scanned imaging LADAR system whose advantage is rapidly imaging cannot work beyond a relatively short operating distance due to the restriction of laser power and attenuation of the signal. Therefore designing a new-type non-scanned heterodyne LADAR system with APD array detector is a imperative solution to this problem. The design of lighting systems is the concentration since different heterodyne efficiencies correspond to different optical systems and then decide the performance of the LADAR system directly. In this paper, it was discussed that the heterodyne efficiency of the system using a single expanded oscillator laser beam lighting system with a single collector lens stays only at 10^{-5} level which is far away from practical applications. Then, as a improvement design, array lighting theory was adopted with a micro lens array collector device played before the detector array, the maximum heterodyne efficiency of which reached 0.82 by calculation. The conclusion drawn in this paper proves the feasibility of array lighting heterodyne LADAR system theoretically and form the foundation for further research on heterodyne LADAR system with APD array detector.

Key words: optical design;　LADAR;　heterodyne detection;　APD array;　heterodyne efficiency
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基于点阵照明的 APD 阵列外差激光雷达外差效率的提高

杨成华，张　勇，赵　远

(哈尔滨工业大学 物理系，黑龙江 哈尔滨 150001)

摘　要： 当前研制的快速成像无扫描激光雷达系统由于激光器功率和信号损耗的限制，遇到了无法增大作用距离的瓶颈。结合光外差体制和 APD 阵列探测器设计的 APD 阵列外差探测激光雷达系统可以有效地解决这个问题。鉴于光学系统的外差效率能够直接影响外差激光雷达的性能，因此照明方式的设计是该套激光雷达系统的一个关键。经过分析，传统的直接扩束照明模式下系统的平均外差效率仅为 10^{-5} 量级，远无法打到使用要求；因此提出了采用改进的点阵照明，并采用在阵列探测器前置微透镜阵列实现匹配接收的方式来解决这一问题。计算结果显示，经过优化后的点阵照明模式下的系统外差效率可达 0.82，进而证明了采用点阵照明设计的 APD 阵列外差激光雷达系统的性能可以达到实用要求，为进一步开展 APD 阵列外差激光雷达的研究工作奠定了理论基础。

关键词： 光学设计；　激光雷达；　外差探测；　APD 阵列；　外差效率

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作者简介： 杨成华(1987-)，男，博士生，主要从事外差激光雷达等方面的研究。Email:yangchenghua110@163.com

导师简介： 赵远(1963-)，男，教授，博士生导师，主要从事激光雷达方面的研究。Email:zhaoyuan@hit.edu.cn

0 Introduction

Non-scanned imaging LADAR system whose advantage is rapidly imaging has become an important subject in the field of LADAR recently. Many researches have made a great progress in the theory of non-scanned imaging LADAR and showed wide range of application prospects in geology, astronomy and military guidance and other fields of this kind of LADAR. However, non-scanned imaging LADAR built by now cannot work beyond a relatively short detection distance with a qualified SNR ratio. This problem has become a main barrier for non-scanned imaging LADAR system to practical applications. Aiming at solving these problems, a series of methods are put forward. For example, army research laboratory developed a Frequency Modulated Continuous Wave(FMCW) LADAR system[1], which is a non-imaging LADAR system based on photoelectric heterodyne theory. Besides, methods such as Amplitude Modulated Continuous Wave (AMCW) LADAR [2], 3 -D range-gating imaging pulsing LADAR with array detector[3], Synthetic-Aperture Ladar[4], synchronous directly detecting LADAR[5] and gain-modulation imaging pulsing LADAR[6] were raised. However, the problems of low SNR and short detection range still remained without obvious improvements. It′s well known that heterodyne is a handling which greatly increases SNR of a detection system. Meanwhile, the performance of current non-imaging LADAR system improves by the use of high sensitive detecting devices especially APD array detectors[7]. By combining both the approaches a heterodyne LADAR system with APD array detector for long distance detection could be designed predictably. To heterodyne LADAR system, heterodyne efficiency which is directly influenced by angle-mismatch, polarization-mismatch as well as phase-mismatch between signal beam and local oscillation beam represents the relationship between SNR ratio and photo-electric field. Due to the difference of SNR and detection range resulting from the design of optical heterodyne system of LADAR, this paper mainly analyses the way to increase the heterodyne efficiency in order to promote SNR ratio and detection range of a heterodyne LADAR system with APD array device. After theoretical analysis, the heterodyne efficiency of such a LADAR system when equipped with a signal expanded beam lighting together with a single collector lens stay at a rather low level (10^{-5}). Then array lighting optical system with a micro lens array collector device are adopted and proven to promote the heterodyne efficiency stupendously, which make the system meet practical requirements.

1 Heterodyne efficiency of heterodyne LADAR system with APD array detector based on single expanded laser lighting system

In single expanded laser lighting system, the heterodyne efficiency of APD element m on the array detector device η_m can be defined as[8]:

$$\eta_m=\cos^2\kappa\frac{\left(e^{i\Delta\phi_m}\iint\limits_{D_m}|U_m||U_{Lm}|\mathrm{d}s\right)^2}{\iint\limits_{\infty}|U_m|^2\mathrm{d}s\iint\limits_{D_m}|U_{Lm}|^2\mathrm{d}s} \tag{1}$$

Where U_m is the distribution of signal field detected by element m, U_{Lm} is the distribution of local oscillator field detected by element m, D_m is heterodyne area of element m, κ is the included angle between the polarization directions of signal beam and local oscillator beam that has nothing to do with the position of APD element, $\Delta\phi_m$ is phase difference in correspondence with the position of APD element.

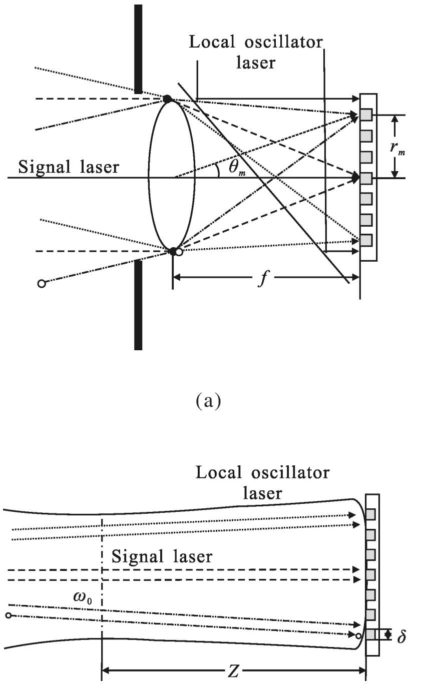
Figure 1 shows the schematic diagram and physical model of ideal heterodyne LADAR receiver. The scattering light signal from the target is a far field weak signal which can be approximated as uniform plane beam and is received by an aperture and a telescope with parameter F. It is drawn by Fraunhofer theory that plane beams from different directions change into overlapping Airy plane beams after diffraction and local oscillator beam is basemode Gauss laser [9]. Based on Eq.(1), the distribution of signal beam and local oscillator beam are:

$$U_r(r,\phi)=\sum_{m=1}^{256} K\left\{\frac{2J_1\left[\dfrac{\pi(r-r_m)}{\lambda F}\right]}{\dfrac{\pi(r-r_m)}{\lambda F}}\right\}\cdot$$

$$\exp\left[\mathrm{j}\left(\frac{ka^2}{2f}+kf\right)-\frac{\pi}{2}\right] \tag{2}$$

$$U_l(r,\phi)=\exp\left(-\frac{r^2}{\omega^2(z)}\right)\exp\left[\mathrm{j}k\left(z+\frac{r^2}{f}\right)-i\phi\right] \tag{3}$$

Where a is the aperture radius of receiving antenna and f is focal distance, r_m is position of APD element relative to the center of the detector. Then we get the heterodyne efficiency of any APD element m:



(a)

(b)

Fig.1 Schematic diagram and physical model of receiving end of heterodyne LADAR system in single expanded laser lighting mode

$$\eta_m=\cos^2\kappa\frac{\left\{\iint\limits_{D_m}\dfrac{2J_1\left[\dfrac{\pi(r-r_m)}{\lambda F}\right]}{\dfrac{\pi(r-r_m)}{\lambda F}}\exp\left(-\dfrac{r^2}{\omega^2(z)}\right)\mathrm{d}s\right\}^2}{\iint\limits_{\infty}\left\{\dfrac{2J_1\left[\dfrac{\pi(r-r_m)}{\lambda F}\right]}{\dfrac{\pi(r-r_m)}{\lambda F}}\right\}^2\mathrm{d}s\iint\limits_{D_m}\left[\exp\left(-\dfrac{r^2}{\omega^2(z)}\right)\right]^2\mathrm{d}s} \tag{4}$$

First of all, the simplest condition is supposed that the girdling of local oscillator beam coincides with the photo surface of detector, which means $z=0$. As a result, the following relations are derived base on laser principle:

$$\omega(z)=\omega_0\sqrt{1+\left(\frac{\lambda z}{\pi\omega_0^2}\right)^2}=\omega_0;R=z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right]\to\infty$$

Adjust local oscillator beam to the same direction of propagation with signal beam, we can derive the following equation after simplification:

$$\eta_m=\frac{8\cos^2\kappa}{\Omega^2}\frac{\left[\int_{x_m}^{x_m+x_0}\exp\left(-\dfrac{x^2}{\Omega^2}\right)J_1(x-x_m)\mathrm{d}x\right]^2}{\exp\left(-\dfrac{2x_m^2}{\Omega^2}\right)-\exp\left[-\dfrac{2(x_m-x_\delta)^2}{\Omega^2}\right]} \tag{5}$$

Considering that scattering light signals in different directions from the target are detected by receiving antenna and converged to Airy disks in corresponding directions onto the photo surface of APD elements. Different APD elements lie in different positions on the detector detect Airy disks with different direction angle and phase. These Airy disks cause both phase delay $\Delta\phi_m$ and space angle-mismatch θ_m. While the general condition is that the girdling of local oscillator beam isn′t on the photo surface of detector, suppose the distance is Z and this distance generates a extra spherical space mismatch θ' and a additional phase delay $\Delta\phi'$. Further revise and simplification is worked on Eq.(5), and the heterodyne efficiency is derived as:

$$\eta_m=\frac{8\cos^2\kappa}{\Omega^2}\frac{\left\{\int_{x_m}^{x_m+x_0}\exp\left(-\dfrac{x^2}{\Omega^2}\right)J_1(x-x_m)\cos\left[\Delta\phi(r_m)-\dfrac{kr_m^2}{2R(Z)}\right]J_0[2F(x-x_m)\theta]\mathrm{d}x\right\}^2}{\exp\left(-\dfrac{2x_m^2}{\Omega^2}\right)-\exp\left[-\dfrac{2(x_m+x_\delta)^2}{\Omega^2}\right]} \tag{6}$$

Where δ is the radius of Airy disk, R is radius of curvature of Gauss beam, θ is the mismatch angle and $\theta=\theta_m-\theta_R=\arctan(r_m/f)-\arctan(r_m/R)$. $\Delta\phi(r_m)$ is phase difference corresponding to r_m, and

$$\Delta\phi(r_m)=\frac{2\pi f}{\lambda}\left(\frac{1}{\cos\theta_m}-1\right) \tag{7}$$

Eq.(6) was programmed first. According to laser principle, there is a minimum of the curvature radius of local oscillator beam on the photo surface of detector. Supposing $z=f=378\,750$ mm for the minimum value of R, $D=100$ mm, $f=250$ mm, $x_0=115$ μm, $\omega_0=11.3$ mm in order to ensure the oscillator beam illuminating the whole 32×32 APD array device with the size 16 mm×16 mm. Then the distribution curve of the heterodyne efficiency is gotten as Fig.2 shows.

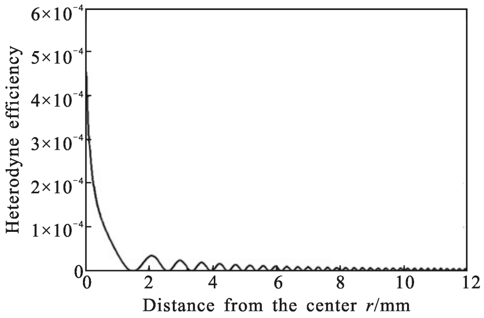


Fig.2 1-D distribution curve of heterodyne efficiency of heterodyne LADAR system in single expanded laser lighting mode

The distribution curves in Fig.2 shows that the value of heterodyne efficiency of a single expanded laser lighting mode heterodyne LADAR system quickly attenuates with the increase of the value of r_m and the heterodyne efficiency of other APD elements stay at only 10^{-5} level. Meanwhile the curves show a decay distribution of the heterodyne efficiency on the array device with a periodical oscillation.

Considering heterodyne theory, there are 3 points to explain the curves in figure except the ignored position difference between Airy disks and the oscillation laser beam, namely polarization-mismatch, angle-mismatch and phase-mismatch.

(1) Polarization-mismatch Since a QWP is usually used in heterodyne systems in order to change linear polarization laser into circular polarization before launch optical system, and then the collected signal beam is recovered as linear polarization before heterodyne with local oscillation beam. This step could effectively reduce polarization-mismatch. As a result, polarization-mismatch in the system mainly comes from the polarization degradation aroused by the combination of signal beam and background light. Here the role of background light is off the table as ideal condition and the homologous, the influence of polarization-mismatch can be ignored.

(2) Angle-mismatch The influence of angle-mismatch reflects in the term:

$$\cos\left[\Delta\phi(r_m)-\frac{kr_m^2}{2R(Z)}\right]$$

Considering current parameters, the variation range of this term is:

$$\frac{kr_m^2}{2R(Z)}\in(0,0.3\pi);\Delta\phi(r_m)=\frac{2\pi f}{\lambda}\left(\frac{1}{\cos\theta_m}-1\right)\in(0,456.4\pi)$$

It is obvious that the variation range is about 230 cycles mainly due to $\Delta\phi(r_m)$, which equals to a mid-frequency oscillation modulation. So the influence of angle-mismatch is embodied in periodical oscillation in the curves in Fig.2.

(3) Phase-mismatch as is known that phase-mismatch is 0 only when the radius of curvature of oscillation Gauss beam equals to the equivalent radius of curvature consisted of Airy signals in different directions. Here define the curve consisted by Airy signals with the same phase after converging the signals reflected by different part of the target as "isophase surface". Since the focal length of receiving lens is $f=250$ mm, the radius of curvature of "isophase surface" is 250 mm too. Meanwhile the radius of curvature of oscillation Gauss beam is:

$$R=z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right]\geqslant 2\frac{\pi\omega_0^2}{\lambda}=7.58\times10^5\text{ mm}$$

which is considerably larger than f. This difference shows the serious phase-mismatch is the principal factor leading to a rapid drop and low value of the heterodyne efficiency of the heterodyne LADAR system in single expanded laser lighting mode.

Due to the low heterodyne efficiency of the heterodyne LADAR system in single expanded laser lighting mode, optimization of the optical system is taken into consideration, which is to say enhance heterodyne efficiency by controlling the parameter Z. Based on Eq.(6), distribution curves of the heterodyne efficiency changing as a function of Z are plotted as shown in Fig.3.

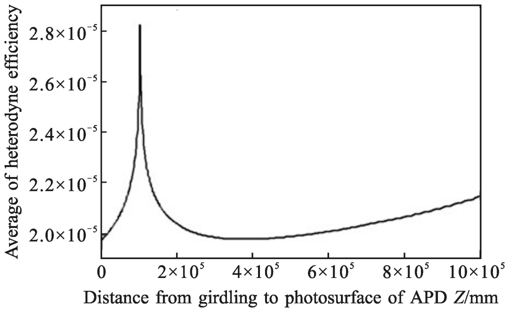


Fig.3 Average value of heterodyne efficiency changes as a function of Z

After analysis of the curves in Fig.3, it is found that though heterodyne efficiency changes as a function of Z and there exist a maximum value within a setting range, while the overall trend of heterodyne efficiency still rest on 10^{-5} and doesn't get significantly improvement. So the conclusion is drown that the performance of heterodyne LADAR system with APD array detector based on single expanded laser lighting system cannot meet the practical requirements.

2 Heterodyne LADAR system with APD array detector of array lighting mode

In view of the conclusion drawn above, a new, modified optical lighting theory is introduced, namely array lighting theory. The principle frame graph of a heterodyne LADAR system with APD array detector of array lighting mode is shown in Fig.4.

The operating principle of the system is as

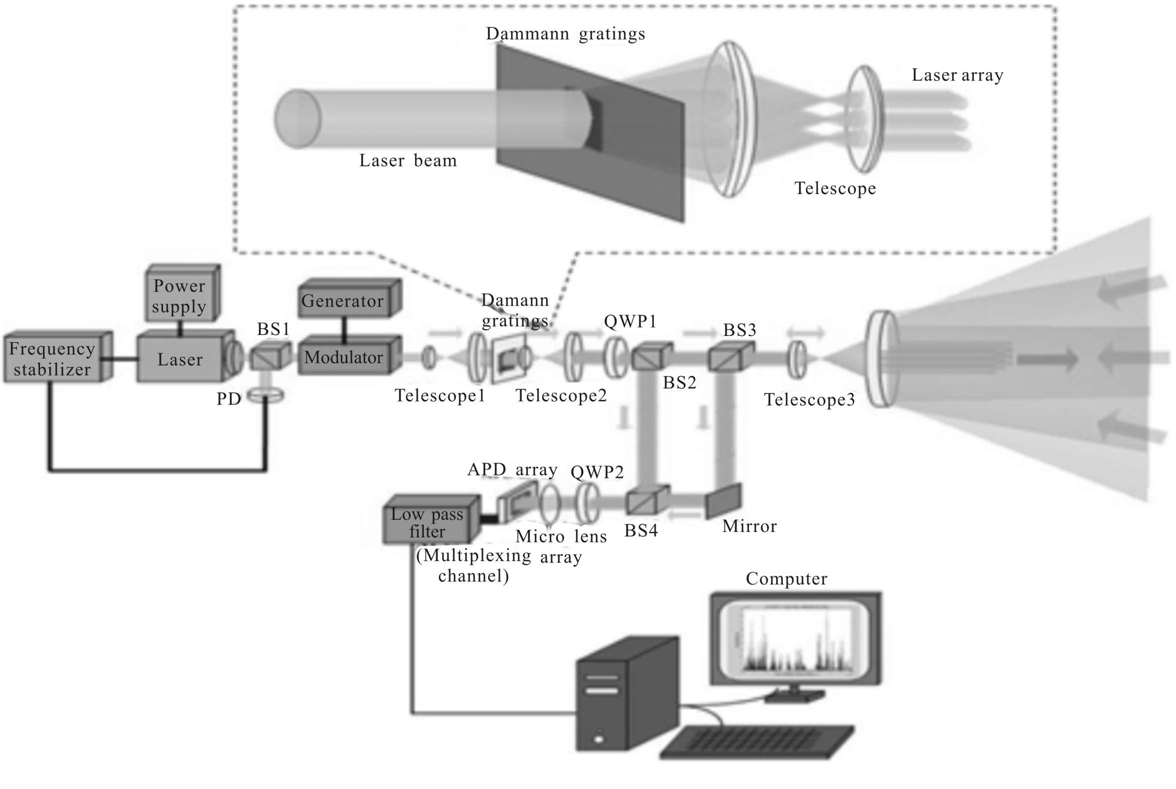


Fig.4 Schematic of heterodyne LADAR system with APD array detector in array lighting mode

follows. Firstly, frequency stabilized single mode linear polarization laser is generated and modulated as chirp modulated continuous signal. Then the signal is shaped into linear polarization laser array all equal to the APD elements of the array detector device by the operation of optical system and Dammann grating. After that the laser array transfer through a QWP and changed into circular polarization. A beam splitter is played to split laser beam into signal beam and local oscillation beam. Signal beam is collimated and expanded by a transceiver illuminating the target. Reflected signal collected by transceiver combines with oscillation beam and is restored to linear polarization by another QWP. Finally the two beam arrays realize heterodyne on the photosurfaces of APD array device and the output electric signals are transferred pass a parallel processing LPF into signal process system.

Array lighting theory is a method that transforms signal beam and local oscillator beam to beam arrays fixed with APD elements on the detector by the use of Diffraction Optical Element (DOE) tthrough the adjustment of telescope and DOE and then realizes heterodyne detection. The schematic of this lighting style is showed in the dashed box in Fig.4 and the physical model of receiving end is showed in Fig. 5.

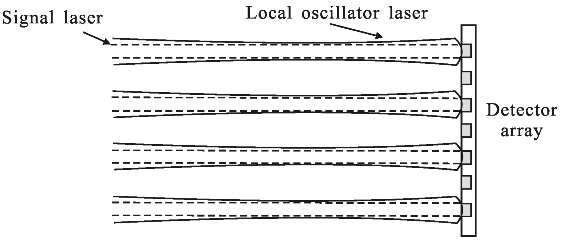


Fig.5 Physical model of receiving end of heterodyne LADAR system in array lighting mode

From these pictures it is found that the laser beams of laser array in array lighting mode are all equal to the APD elements of the array detector device, which avoids the serious phase-mismatch between signal beam and oscillation beam caused by expansion of oscillation beam in single expanded laser lighting mode. Thus by use of array lighting theory the heterodyne efficiency of a heterodyne LADAR system with APD array would be far superior to the former lighting mode.

Another advantage of array lighting theory is the possibility of further enhancement of the heterodyne efficiency by optical optimization. That means it can realize perfect match when adjusting the girdling of oscillation beam to the photosurface of APD element by changing the F number. Similar with the analysis above, the heterodyne efficiency of element m on the APD array detector is gotten:

$$\eta=\frac{8}{\Omega^2}\cos^2\kappa\frac{\left[\iint_0^{x_0}\exp\left(-\frac{x^2}{\Omega^2}\right)J_1(x)J_0(2Fx\theta)\cos\frac{kr^2}{2R}\mathrm{d}x\right]^2}{1-\exp\left[-2\left(-\frac{x_\delta}{\Omega}\right)^2\right]} \tag{8}$$

And from Eq.(8) an isovalent equation could be drawn as follow for conciseness:

$$\eta=\eta(\kappa,z,F,\theta) \tag{9}$$

According to single-point optical heterodyne theory, a optical system that satisfies space collimation between signal beam and local oscillator beam ($\theta=0$) and transforms launched laser to circularly polarized light($\kappa\to0$) and $z=0$, $R\to\infty$ could be designed, which corresponding to the maximum value of heterodyne efficiency as follow:

$$\eta=\eta(F)=\frac{8}{\Omega^2}\frac{\left[\iint_0^{x_0}\exp\left(-\frac{x^2}{\Omega^2}\right)J_1(x)\mathrm{d}x\right]^2}{1-\exp\left[-2\left(\frac{x_\delta}{\Omega}\right)^2\right]} \tag{10}$$

In this equation, $\Omega=\pi\omega_0/\lambda F$. As is shown that heterodyne efficiency in array lighting mode becomes a unary function of F. Programming Eq. (10) by MATLAB, and distribution curves of the heterodyne efficiency is gotten as Fig.6 shows.

Seen from simulated result of Fig.6, heterodyne efficiency in array lighting mode reaches a maximum value about 0.82 when F is around 4, which is in conformity with the theoretical maximum value.

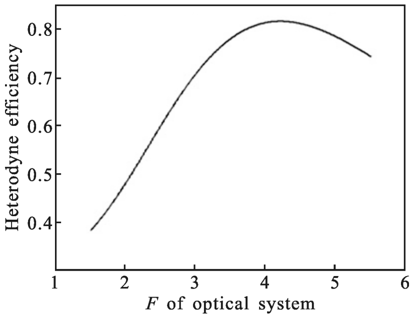


Fig.6 Heterodyne efficiency changes as a function of F in array lighting mode

3 Conclusion

In this paper, heterodyne efficiency of both single expanded laser lighting theory and array lighting theory are derived respectively and corresponding numerical simulation experiments are made. The result shows that the value of heterodyne efficiency of a single expanded laser lighting mode heterodyne LADAR system quickly attenuates with the increase of the value of r_m and maintain a relatively low 10^{-5} order without a possibility of progress by optimization design of the optical system, which is aroused by the serious phase-mismatch between signal beam and oscillation beam caused by expansion of oscillation beam.

On the other hand, because of avoidance of that serious phase-mismatch, heterodyne efficiency in array lighting mode is dramatically enhanced and reaches a maximum value about 0.82 when F is around 4, which is in conformity with the theoretical maximum value. The conclusion drawn in this paper proves the feasibility of array lighting heterodyne LADAR system theoretically and forms the foundation for further practicability research on heterodyne LADAR system with APD array detector.

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